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Coal Gasification Environmental Data Summary: Sulfur and Nitrogen Species

Radian Corp., Austin, TX

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Research Triangle Park, NC

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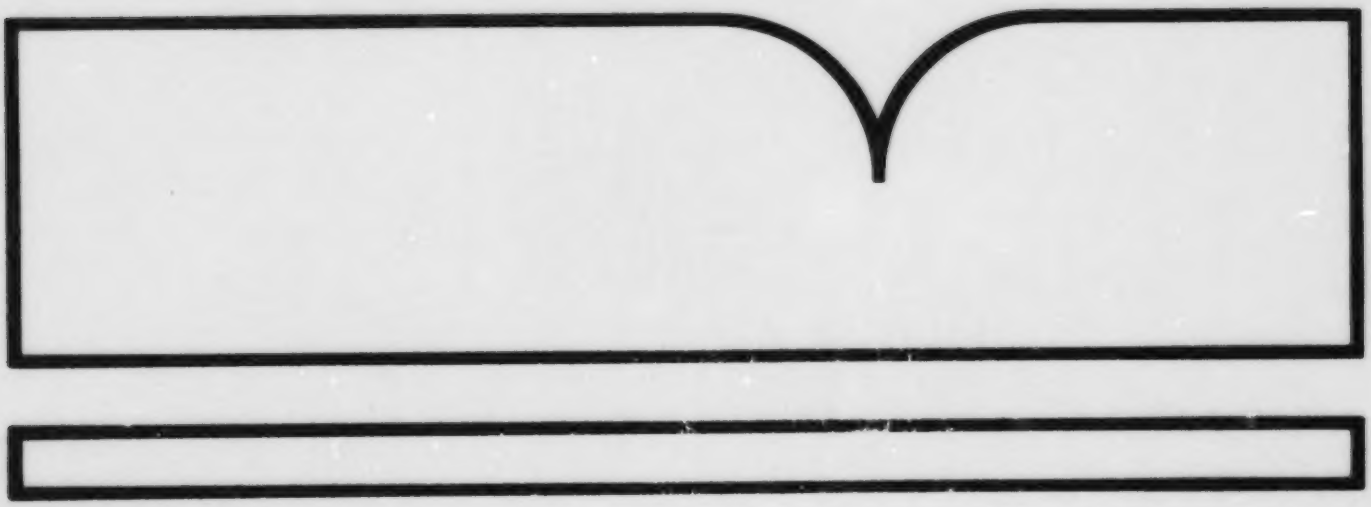

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April 1986

COAL GASIFICATION

ENVIRONMENTAL DATA SUMMARY:

SULFUR AND NITROGEN SPECIES

by

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EPA Contract No. 68-02-3137

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ABSTRACT

This report contains a summary of the data on sulfur and nitrogen species from the source test and environmental assessment studies of low- and medium-Btu gasification processes which were sponsored by the Air and Energy Engineering Research Laboratory of the U.S. Environmental Protection Agency from 1977 to 1981. The data presentation is focused on the composition and distribution of the major streams from the gasifier unit. Material accountability, elemental distribution, and species distributions are included for sulfur and nitrogen. Consistent trends in the collected data, comparison with the results of some laboratory studies, and correlations with some fundamental chemical relationships are given.

CONTENTS

Abstract iii
Figures vi
Tables viii

1. Introduction 1
2. Summary 3
3. Process Descriptions 9
   Introduction 9
   Summary and comparison of gasification operations 14
   Summary and comparison of downstream processing operations . 20
4. Sulfur and Nitrogen Distribution Summary 31
   Vapor phase distributions 35
   Aqueous species 40
   Solid streams 42
5. Relationships and Correlations 50
6. Data Summary 62

References 70
Appendix, Gasifier Flow Rate Data 72

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FIGURES

Number		Page
1	Sulfur accountability	4
2	Nitrogen accountability (excluding N_2)	7
3	Nitrogen accountability (including N_2)	8
4	Conceptual configurations of different gasifier bed types	18
5	Comparative coal feedstock analyses, dry basis, wt. %	21
6	Comparative gasifier feed rates, g/sec-gasifier	22
7	Comparative gasifier feed ratios, kg/kg	23
8	Simplified block flow diagram of Chapman gasifier	25
9	Simplified block flow diagram of Wellman-Galusha (Ft. Snelling) gasifier	25
10	Simplified block flow diagram of Wellman-Galusha (Glen-Gery) gasifier	26
11	Simplified block flow diagram of Riley gasifier	26
12	Simplified block flow diagram of Foster-Wheeler/STOIC gasifier	27
13	Simplified block flow diagram of Lurgi-type gasifier	27
14	Simplified block flow diagram of KRW PDU gasifier	28
15	Simplified block flow diagram of Koppers-Totzek (Modderfontein) gasifier	28
16	Simplified block flow diagram of Koppers-Totzek (Ptolemais) gasifier	29
17	Simplified block flow diagram of Texaco/Ruhrchemie gasifier	29
18	Sulfur distribution among outlet streams	32

FIGURES (Continued)

Number		Page
19	Nitrogen distribution among outlet streams (excluding N_2)	34
20	Distribution of vapor phase sulfur species	36
21	Distribution of vapor phase nitrogen species	39
22	Distribution of sulfur species in aqueous streams that contact ash or slag	41
23	Distribution of sulfur species in aqueous streams	43
24	Distribution of nitrogen species in aqueous streams that contact ash or slag	44
25	Distribution of nitrogen species in aqueous streams	45
26	Distribution of sulfur in solid streams	47
27	Distribution of nitrogen in solid streams	49
28	Relationship between coal sulfur and product gas sulfur	51
29	Product gas sulfur species comparisons	53
30	Concentration ratios for hydrogen sulfide/carbonyl sulfide conversion reactions	54
31	Production factors, vapor phase sulfur	57
32	Relationship between coal nitrogen and product gas nitrogen	58
33	Product gas nitrogen species comparison	60
34	Production factors, vapor phase nitrogen	61

TABLES

Number		Page
1	Comparison of Coal Gasification Facilities	11
2	Sulfur Distribution	63
3	Nitrogen Distribution	64
4	Average Composition: Product Gas	65
5	Average Composition: Aqueous Discharges	67
6	Average Composition: Solids	68
7	Sulfur Speciation of Solids from the KRW PDU	69
A-1	Chapman Gasifier Stream Flow Rate Data	72
A-2	Wellman-Galusha (Fort Snelling) Gasifier Stream Flow Rate Data	73
A-3	Wellman-Galusha (Glen-Gery) Stream Flow Rate Data	74
A-4	Riley Gasifier Stream Flow Rate Data	75
A-5	Foster-Wheeler/STOIC Gasifier Stream Flow Rate Data	76
A-6	Lurgi-Type Gasifier Stream Flow Rate Data	77
A-7	KRW PDU Gasifier Stream Flow Data	78
A-8	Koppers-Totzek Gasifier Stream Flow Rate Data	79
A-9	Texaco Gasifier Stream Flow Rate Data	80

SECTION 1

INTRODUCTION

The ultimate fate of the sulfur and nitrogen in coal gasification processes is a recognized environmental concern. Future commercial designs for sulfur removal units, ammonia stripping processes, and wastewater treatment systems for coal-based synthetic fuels plants will be based on test data from pilot-scale facilities and discharge estimates calculated from the existing technology data base. The purpose of this document is to present a compilation and review of the data on sulfur and nitrogen available from the U.S. Environmental Protection Agency funded environmental assessment of gasification processes to facilitate data access and to provide a more cohesive basis for understanding the fate of these components in gasification.

The gasification processes discussed here were selected based on the greater availability of process, gas, liquor, and solid phase data. The majority of the data presented in this report are from:

- Chapman gasifier (1)--Holston Army Ammunition Plant, Kingsport, Tennessee;
- Wellman-Galusha gasifiers--Glen-Gery (2) Brick Company, York, Pennsylvania and U.S. Bureau of Mines, Twin Cities Metallurgy Research Center (3), Fort Snelling, Minnesota;
- Riley gas producer (4)--Riley Stoker Corporation, Worcester, Massachusetts;
- Foster-Wheeler/STOIC gasifier (5)--University of Minnesota, Duluth, Minnesota;

- Lurgi-type gasifier (6)--Kosovo, Yugoslavia;
- Koppers-Totzek gasifiers--Ptolemais, Greece (7) and Modderfontein, South Africa (8);
- Texaco gasifier (9)--Ruhrkohle/Ruhrchemie, Oberhausen-Holten, Federal Republic of Germany; and
- Kellogg Rust/Westinghouse gasifier (10)--Waltz Mill, Pennsylvania.

Data are available on varied sulfur and nitrogen species in many gasification process and discharge streams. However, not all of the source test facilities from which the data were collected are at the same level of development nor were the various test programs conducted to provide uniform data sets for comparison among processes. Therefore, by necessity, the distribution and fate of the coal sulfur and nitrogen among the major output streams from each gasifier have been selected as the basis for this review. Data from bench-scale units and laboratory models, although fundamental and necessary, have been excluded from this report. Thus, only data from pilot-scale or larger size units have been included.

The most comprehensive data set available is for the vapor phase species. Data on sulfur and nitrogen species present in aqueous output streams are available for most of the gasification processes listed previously. The aqueous species are important to the design and operation of commercial facilities. However, flow data for the aqueous streams in the smaller pilot-scale facilities generally were estimated to be so low as not to contribute significantly to the facility mass balance approximations. Very few data are available on the chemical forms of the sulfur and nitrogen present in the ash or slag from these processes. The leaching characteristics of these solid effluents under various regimes along with the sulfur and nitrogen species present in the leachates are to be discussed in a separate document.

SECTION 2

SUMMARY

The majority of the total sulfur and nitrogen present in the coal is converted to gaseous species during the gasification process. The product gas contains the majority of the sulfur leaving the gasification process and the majority of the product gas sulfur is in the form of hydrogen sulfide. The most consistent trend apparent in the overall gasification distributions reviewed here is that of the volatile sulfur species. Between 82 and 94 percent of the vapor phase sulfur from eight of the gasification processes reviewed is present as hydrogen sulfide. Only minimal amounts of the coal sulfur exit the gasifier in the process water, and the ash/slag and cyclone dust each accounted for less than 10 percent of the total outlet sulfur. Section 4 provides a detailed discussion of the sulfur and nitrogen distribution for each process.

The fate of coal sulfur in gasification processes generally is well defined by the available data. Ten of the eleven gasification tests reviewed have a sulfur mass accountability within $\pm$20 percent. Since the data acquisition periods were relatively short, 24 to 48 hours in most cases, this degree of accountability with limited time-phasing and replication of samples should be considered quite satisfactory. Sulfur mass accountability was poor at the Chapman facility (less than 40 percent). This may have been due in part to the experimental techniques in use at that time (1977) which were not well refined. Insufficient data were available from the Koppers-Totzek facility at Modderfontein to provide an estimated sulfur balance. Figure 1 presents a summary of the sulfur mass accountability data for the 11

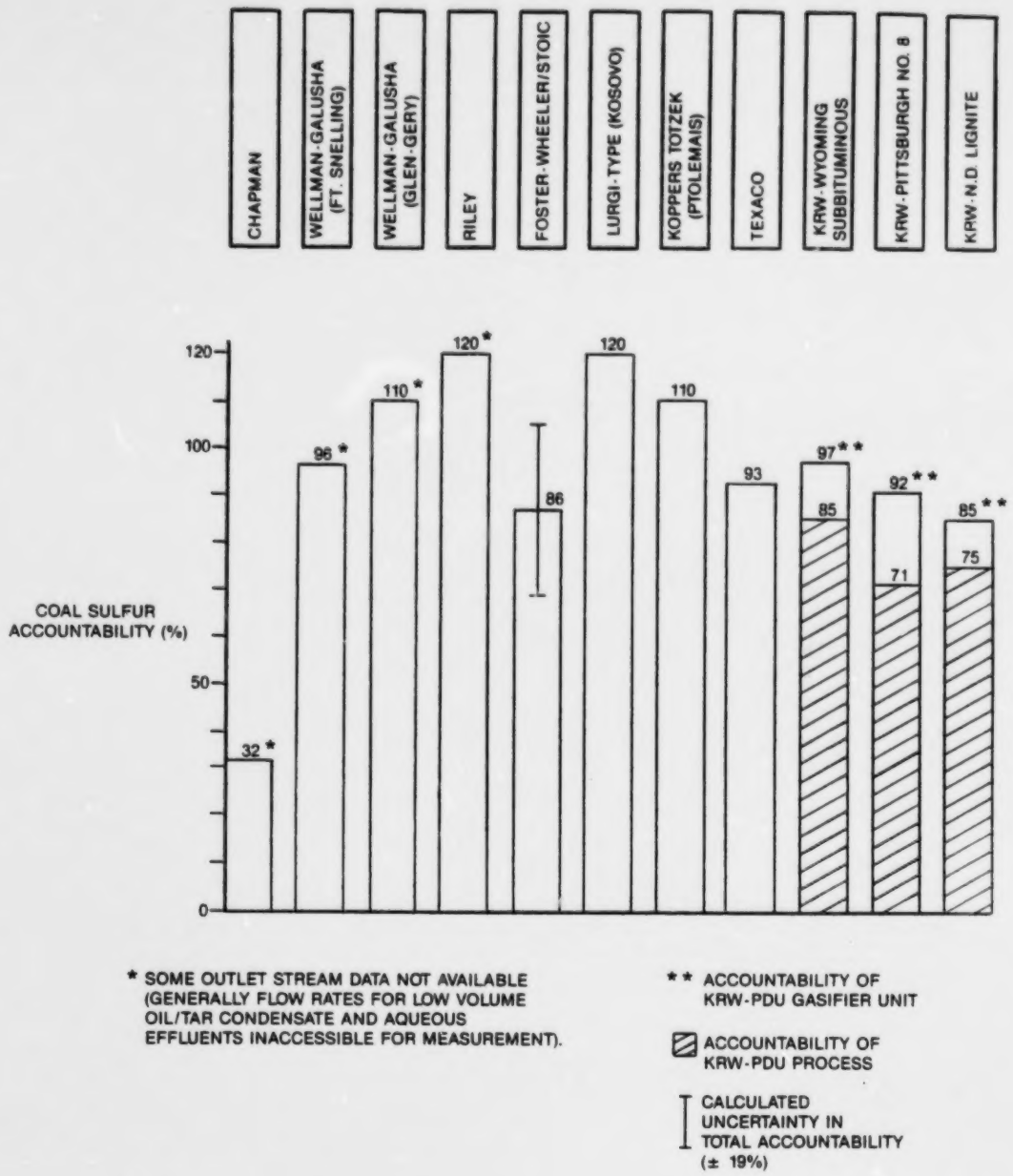


Figure 1. Sulfur accountability.

gasification tests reviewed. The calculated uncertainty in the overall accountability is shown in the figure for one of the facilities (Foster-Wheeler/STOIC). The uncertainty in the accountability was not determined for all of the processes presented. However, the uncertainty in the process measurements and analytical data are considered to be similar for the other tests and, therefore, the uncertainty in the overall accountability to be of similar magnitude.

The fate of coal nitrogen is less clear. Five of the processes reviewed were air blown low-Btu gas producers. Therefore, the mass of diluent nitrogen in the air feed far outweighed the coal nitrogen. Nitrogen species distributions in the raw product gases are very similar for the four low-Btu processes for which data are available. Ammonia accounts for 81 to 87 percent of the vapor phase nitrogen (excluding N_2) with the remaining measured nitrogen present as cyanide. No vapor phase volatile amines or other low molecular weight organo-nitrogen species determinations were reported for these processes.

Calculating coal nitrogen accountability by excluding diluent N_2 in the feed air or N_2 contaminant in the oxygen feed as in the Kosovo facility and excluding diluent N_2 in the product gases yields low overall accountability ranging from less than three percent to approximately 70 percent. Total inlet nitrogen accountability is better with seven of the eleven process tests showing total nitrogen mass accountability within 10 percent. Some of the coal nitrogen may be converted to N_2 during gasification. With large N_2 feed rates relative to the coal nitrogen feed rate, this conversion becomes immeasurable at the production scale of these facilities. The low accountability for coal nitrogen when diluent N_2 is excluded is not an *a priori* proof of the magnitude of conversion of coal nitrogen to N_2. The total nitrogen accountability for the Texaco process at Ruhrchemie provides a partial proof of very low coal nitrogen conversion to N_2. At that facility an extremely small amount of N_2 enters the system as an impurity in the feed oxygen. The coal nitrogen is found predominantly (85%) in the raw product gas as reactive species; however, a small amount of N_2 is detected in the

product gas. Figure 2 summarizes the coal nitrogen accountability with the exclusion of N_2; Figure 3 presents the total nitrogen accountability for each facility (including N_2).

As stated previously, some of the mass accountability data may have been affected adversely by the relatively unsophisticated experimental techniques in use at the time. The data compiled in this summary report originated from gasification test and evaluation projects conducted over eight years. During this time, the measurement techniques and quality control requirements were modified and evolved such that no single consistent set characterizes all of the data. The quality control procedures described in Section 7 are generally applicable to these data.

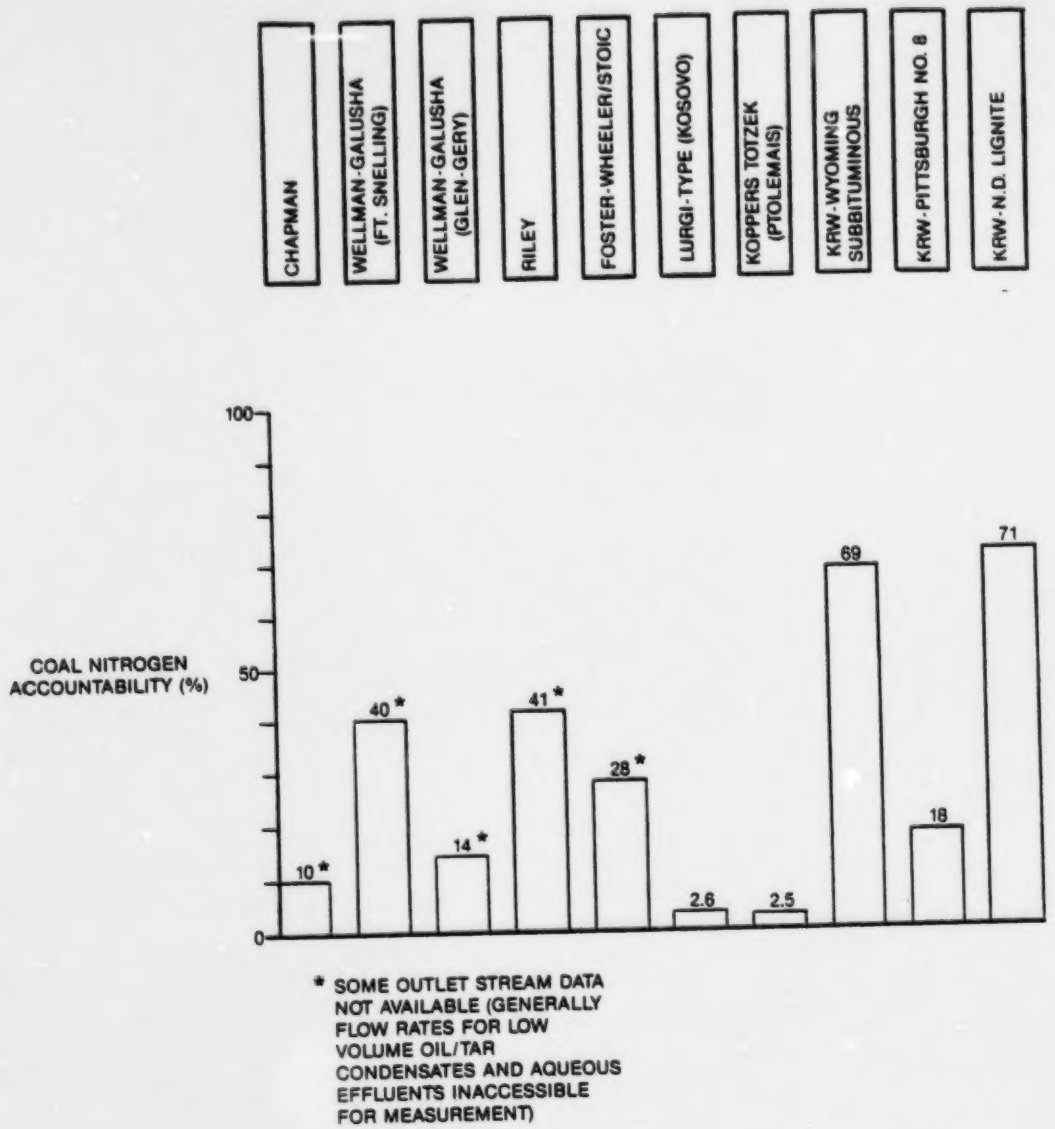


Figure 2. Nitrogen accountability (excluding N_2).

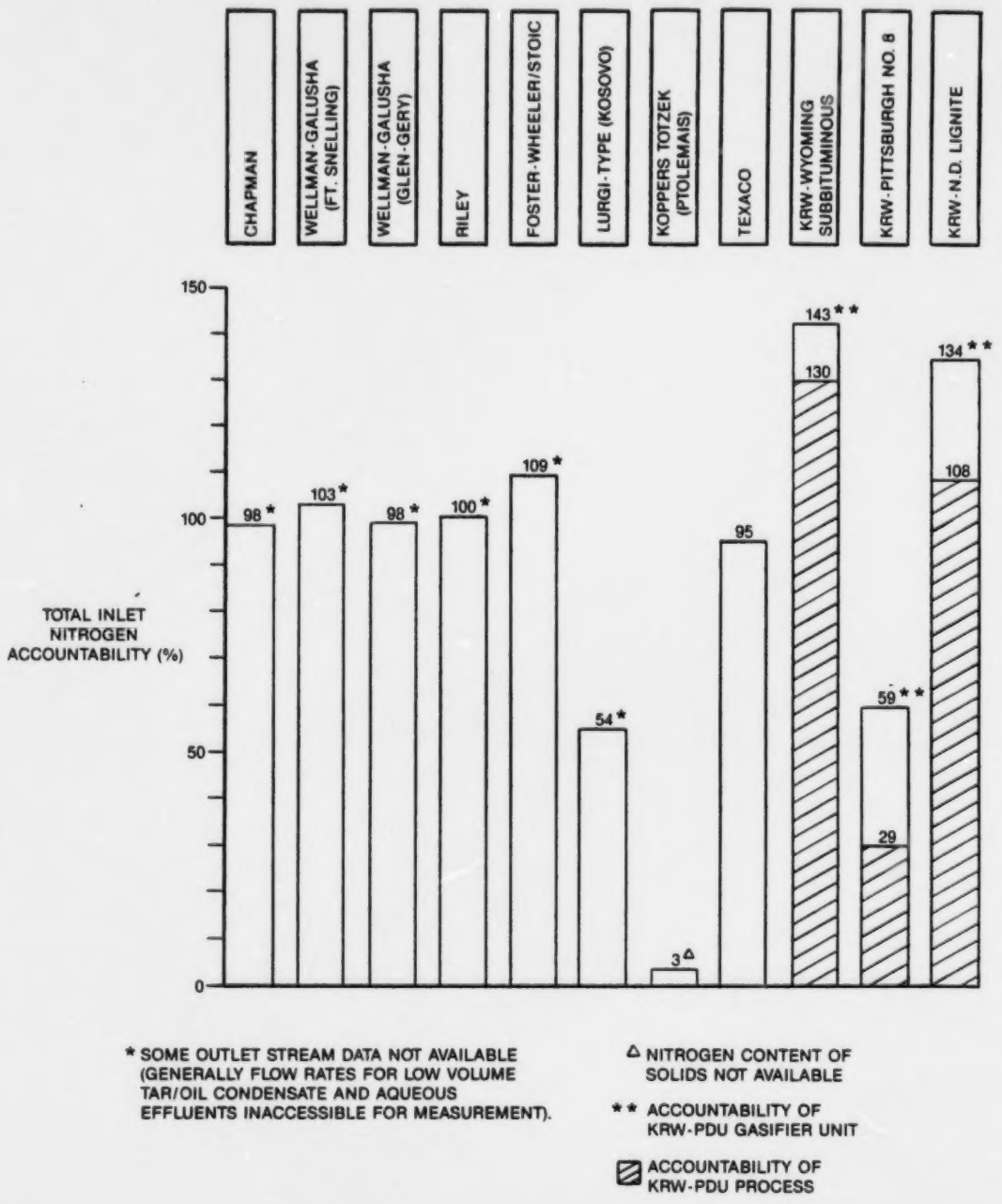


Figure 3. Nitrogen accountability (including N_2).

SECTION 3

PROCESS DESCRIPTIONS

INTRODUCTION

This section presents brief descriptions and comparisons of the coal gasification facilities for which data are presented in this report. The following types of gasifiers and facilities are included:

- Chapman low-Btu industrial gasifiers at Kingsport, Tennessee;
- Wellman-Galusha low-Btu gasifiers at the Bureau of Mines Twin Cities Metallurgy Research Center, Fort Snelling, Minnesota, and Glen-Gery Brick Company, York, Pennsylvania;
- Riley Gas Producer low-Btu gasifier at Worcester, Massachusetts;
- Foster-Wheeler/STOIC low-Btu industrial gasifier at the University of Minnesota, Duluth (UMD);
- Lurgi-type medium-Btu commercial gasifiers at Kosovo, Yugoslavia;
- Kellogg-Rust/Westinghouse (KRW) medium-Btu gasifier PDU at Madison, Pennsylvania;
- Koppers-Totzek medium-Btu commercial gasifiers at Modderfontein, South Africa;

- Koppers-Totzek (GKT) medium-Btu commercial gasifier at Ptolemais, Greece; and

- Texaco medium-Btu demonstration gasifier at the Ruhrkohle/Ruhrchemie facility in Oberhausen-Holten, Federal Republic of Germany.

Table 1 presents a summary of the features of the coal handling/preparation, coal feeding, gasification, and downstream processes (including gas cleanup and ash removal/handling) present at each facility. The similarities and differences will be discussed in more detail later; however, some of the salient differences between processes are summarized below:

- Oxygen versus Air-Injection: Gasifiers that use air as their source of oxygen produce a gas having a lower calorific value than those that use pure or nearly pure oxygen. This is due to the nitrogen diluent present in air. Chapman, Wellman-Galusha, Riley, and Foster-Wheeler/STOIC gasifiers are of the so-called "low-Btu" type, while the Koppers-Totzek and Texaco gasifiers both produce "medium-Btu" gas. The Lurgi and KRW gasifiers can be operated in either mode; the data presented here were obtained on systems producing medium-Btu gas.

- Bed Type: There are three principal gasifier bed types: moving-bed, fluidized-bed, and entrained-bed. Moving-bed (sometimes referred to as fixed-bed) gasifiers feature a layer of coal which is generally supported on a grate through which air (or oxygen) and steam are passed. In thin bed systems, less than a 0.5 m layer of coal is maintained on the coal grate. In thick bed systems, bed depths of 2 to 5 m are more typical. The direction of movement of the coal relative to the gas is countercurrent. In fluidized-bed gasifiers the upward velocity of the gas stream is such that the fluid drag forces nearly balance the downward forces due to the weight of the coal/ char particles. The particles act as if they were a turbulent fluid. In entrained-bed gasifiers,

TABLE 1. COMPARISON OF COAL GASIFICATION FACILITIES

	Chapman	Wellman-Galusha (Fort Snelling)	Wellman-Galusha (Glen-Gery)	Riley	Foster-Wheeler/ STOIC
COAL HANDLING					
Receive presized coal	X	X	X	X	X
Crush/pulverize					
Screen		X			
Thermal drying					X
Slurrying					
Air classifying					
COAL FEEDING					
Lock hoppers		X	X	X	X
Screw feed/entrainment					
Slurry pumping					
Barrel valve	X				
GASIFICATION					
Atmospheric (A)/Pressurized (P)	A	A	A	A	A
Moving- (M)/Fluid- (F)/Entrained-bed (E)	M	M	M	M	M
Thin bed (T)/Deep bed (D)	T	D	D	T	D
Slagging (S)/Agglomerating (A)/ Dry ash (D)	D	D	D	D	D
Single-stage (S)/Two-stage (T)	S	S	S	S	T
Cocurrent (C)/Countercurrent (CC)	CC	CC	CC	CC	CC
Air blown (A)/O_2 blown (O)	A	A	A	A	A
GAS CLEANUP					
Cyclones	X	X	X	X	X
ESP					X
Quench/Scrubbing	X				
Acid gas removal					
ASH REMOVAL/HANDLING					
Lockhoppers					
Ash plow	X			X	X
Slide valve		X	X		
Water quench	X	X	X	X	X
Conveyor/Drag chain	X				X

(continued)

TABLE 1. COMPARISON OF COAL GASIFICATION FACILITIES (Continued)

	Lurgi-type (Kosovo)	KRW PDU	Koppers-Totzek (Modderfontein)	Koppers-Totzek (Ptolemais)	Texaco (Ruhrchemie)
COAL HANDLING					
Receive presized coal					
Crush/pulverize	X	X	X	X	X
Screen	X				
Thermal drying	X	X	X	X	
Slurrying					X
Air classifying		X			
COAL FEEDING					
Lock hoppers	X	X			
Screw feed/entrainment			X	X	
Slurry pumping					X
Barrel valve					
GASIFICATION					
Atmospheric (A)/Pressurized (P)	P	P	A	A	P
Moving- (M)/Fluid- (F)/Entrained-bed (E)	M	F	E	E	E
Thin bed (T)/Deep bed (D)	D	D	-[a]	-[a]	-[a]
Slagging (S)/Agglomerating (A)/Dry ash (D)	D	A	S	S	S
Single-stage (S)/Two-stage (T)	S	S	S	S	S
Cocurrent (C)/Countercurrent (CC)	CC	CC	C	C	C
Air blown (A)/O_2 blown (O)	O	O	O	O	O
GAS CLEANUP					
Cyclones		X			
ESP			X	X	
Quench/Scrubbing	X	X	X	X	X
Acid gas removal	X		X	X	X
ASH REMOVAL/HANDLING					
Lockhoppers	X	X			X
Ash plow					
Slide valve					
Water quench	X		X	X	X
Conveyor/Drag chain	X		X	X	X

[a]Not applicable.

the coal and gases move in the same direction (co-current). Of the gasifiers represented here, only the KRW is a fluidized-bed gasifier; entrained-bed gasifiers include the Koppers-Totzek and Texaco gasifiers. All the rest are of the fixed-bed type.

- Single-stage versus Two-stage: In single-stage gasifiers, the raw product gas is taken off at a single location. In two-stage gasifiers, two separate raw product gas streams are generated. In a fixed-bed, two-stage design the upper gas product is richer in heavier hydrocarbon gases and aerosols formed by the release of coal volatile matter and water vapor resulting from the release of moisture in the feed coal. The lower gas product is richer in lighter combustible gases such as carbon monoxide and hydrogen. The only two-stage gasifier presented here is the Foster-Wheeler/ STOIC gasifier.

- Atmosphere Pressure versus Elevated Pressure: Operation at elevated pressure allows the use of smaller vessels for equivalent gas production. Increased partial pressures of reactive gases may increase reaction rates and/or alter reaction equilibria in both the gasifier and in downstream units. Additional effects of pressurized operation include:

  --reduced needs for compression of raw gas prior to downstream treatment units (e.g., physical absorption type acid gas removal processes) or prior to injection into a pipeline transmission system.

  --generation of flash gases from depressurization of by-product liquids, resulting in an additional waste gas stream.

  Of the gasifiers considered here, only three were operated at elevated pressure; the Lurgi-type (Kosovo), KRW, and Texaco

(Ruhrkohle/Ruhrchemie) gasifiers. The rest were operated at or near atmospheric pressure.

The remainder of this process description section consists of two subsections: the first discusses and compares the gasification processes (including coal preparation and coal feeding), while the second deals with downstream processing operations.

SUMMARY AND COMPARISON OF GASIFICATION OPERATIONS

Coal gasification involves the conversion of coal to gaseous species which can be burned as fuels or which can be used as feedstocks in the formation of fuels or other products. There are several general types of phenomena which occur during coal gasification which are common to all processes. These include coal drying and devolatilization, gasification, oxidation (or combustion), water-gas shift, volatilization and reaction of coal sulfur and nitrogen, and production of unreacted residuals (ash). Each of these may occur in different areas of the gasification reactor depending on the method used to contact the coal and the reactant gases.

Drying and Devolatilization

As the coal is heated, moisture is given off and the volatile fraction undergoes pyrolysis (i.e., thermal decomposition). The composition of the volatiles (some of which may be liquids or even solids at ambient conditions) depends on a number of factors including coal rank, coal particle thermal history (e.g., heating rate, duration of heating, and final temperature reached), and the composition and pressure of the reactant gas. Anthracite, for example, gives off relatively little volatile matter compared with bituminous coal or lignite. If devolatilization occurs at relatively low temperatures, the volatile fraction contains appreciable amounts of tar and oil aerosols. If devolatilization occurs at higher temperatures, these tars and oils are largely converted, by further pyrolysis into lighter hydrocarbons, methane, hydrogen, carbon monoxide, and carbon dioxide.

Gasification

In the gasification zone, various reactions occur between the carbon in the coal and the hot gases present in the oxidation zone. The principal gasification reactions of interest are:

$$C + CO_2 + \text{heat} \longrightarrow 2CO$$

$$C + H_2O + \text{heat} \longrightarrow CO + H_2$$

$$C + 2H_2 \longrightarrow CH_4 + \text{heat}$$

As can be seen, the primary products of gasification are carbon monoxide, hydrogen, and methane. The energy required by the first two reactions is furnished by the sensible heat of the gases leaving the oxidation zone. The extent to which these competing reactions proceed to completion depends on factors such as pressure, temperature, residence time, and reactant concentrations.

Oxidation (Combustion)

Oxidation involves the heterogeneous reaction between coal carbon and oxygen to produce CO and CO_2:

$$C + O_2 \longrightarrow CO_2 + \text{heat}$$

$$C + 1/2\ O_2 \longrightarrow CO + \text{heat}$$

These reactions result in the release of energy that allows the gasification reactions to proceed. The ratio of carbon monoxide to carbon dioxide formed in the oxidation zone depends on the oxygen partial pressure and the temperature. If excess oxygen is present, some of the carbon monoxide will be converted to CO_2 by gas phase oxidation.

In addition, in entrained-bed gasifiers and some fluidized-bed gasifiers where devolatilization occurs in an oxygen-rich environment, tars and oils and other organics are also oxidized in the gas phase, forming carbon monoxide, carbon dioxide, and hydrogen.

Water-Gas Shift

An important gas-phase reaction occurring in the gasifier involves the equilibrium among carbon monoxide, carbon dioxide, hydrogen, and water vapor:

$$CO + H_2O \rightleftharpoons CO_2 + H_2$$

The composition of the raw product leaving the gasifier is significantly influenced by this equilibrium. High temperature favors the formation of carbon monoxide and water vapor. The relative partial pressures of the various reactants also influence the equilibrium composition.

Sulfur and Nitrogen Reactions

Coal contains varying amounts of sulfur and nitrogen. Significant reaction products formed from these elements during gasification include ammonia, hydrogen cyanide, hydrogen sulfide, carbonyl sulfide, and other organic sulfur species (such as mercaptans). The quantities of such species formed depend on a number of factors including coal sulfur and nitrogen content, temperature, pressure, and hydrogen concentration in the gas. The ratio of carbonyl sulfide to hydrogen sulfide is a particularly important concern because this ratio can affect the selection, design, and performance of downstream acid gas removal and sulfur recovery processes. As with the water-gas shift reactions discussed above, the ratio of COS to H_2S in the raw gas is affected by the steam and carbon dioxide content of the gas due to the chemical equilibrium which is maintained at high temperatures among these four species:

$$H_2S + CO_2 \rightleftharpoons COS + H_2O$$

Similar relationships may also hold for nitrogen species such as ammonia and hydrogen cyanide.

Solid Waste

Coal contains substantial quantities of nonreactive mineral matter which remains after the coal has been gasified. The resulting solid waste will be in the form of ash or solidified slag droplets, depending primarily on the reactor operating temperature and the ash fusion point. Fixed-bed gasifiers can be operated to produce either a "dry", unfused ash (low-temperature operation) or a fused slag by-product (high-temperature operation). Entrained-bed gasifiers operate at high temperatures and produce a slag by-product. Some fluidized-bed gasifiers operate at a temperature at which the ash particles are soft and sticky and form agglomerates that are removed from the gasifier. Some of the mineral matter components may also be volatilized; the extent to which this occurs depends on the temperature and the chemical forms in which these compounds are found in the coal.

The susceptibility to leaching of the species remaining in the ash or slag is also likely to vary depending on their solubility and the ease with which water can penetrate the solid. For example, fused slags are less subject to leaching than more porous ash particles.

Figure 4 shows the conceptual zones into which fixed-bed, fluidized-bed, and entrained-bed gasifiers may be divided. Note that in the fixed-bed and fluidized-bed gasifiers, the relative direction of gas and solid flows is countercurrent, while it is co-current in the entrained-bed gasifier. Also note the differences in the order of the various reaction zones.

Associated closely with the gasification operation are the equipment and operations required to prepare the coal and feed it into the gasifier

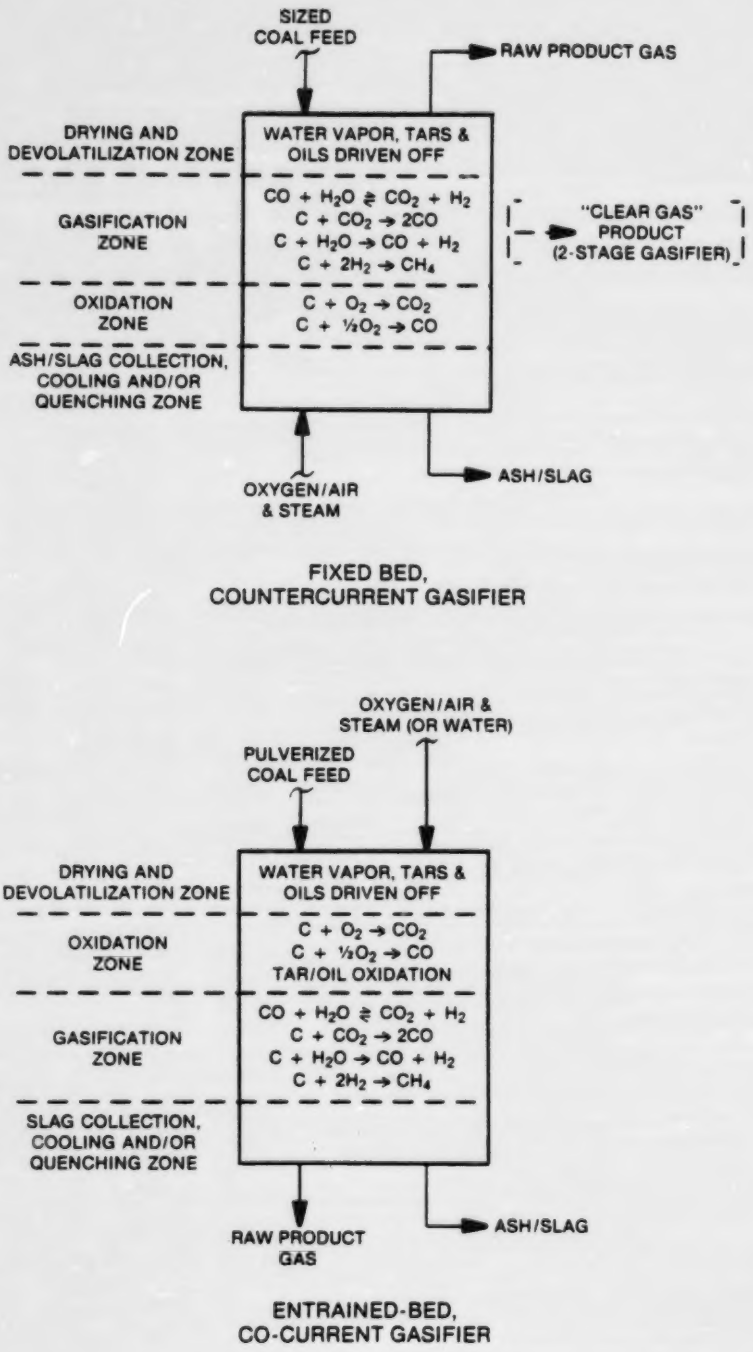


Figure 4. Conceptual configurations of different gasifier bed types.

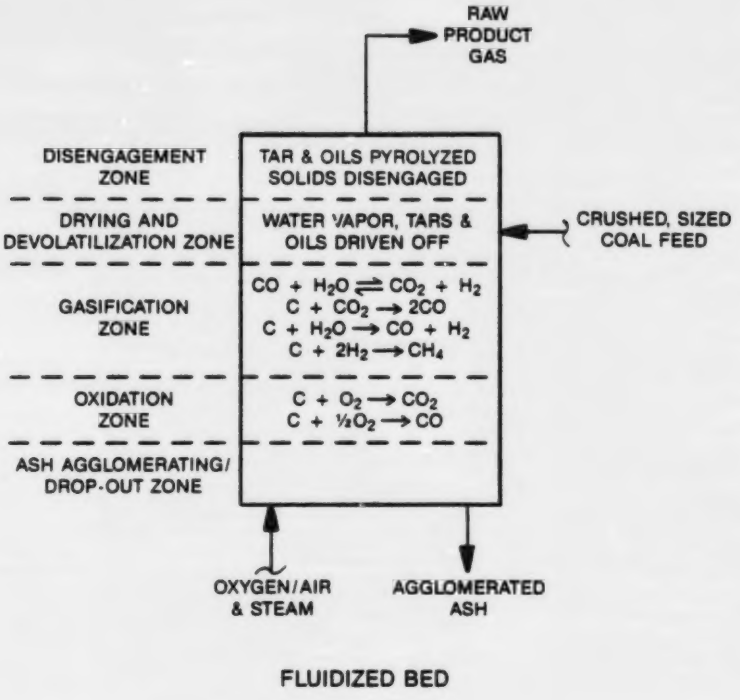


Figure 4. (Continued)

vessels. In the case of most small, low-Btu gasification facilities, very limited coal preparation is performed. These facilities typically gasify coal which has been sized prior to its delivery to the site. Some screening of the coal for removal of fines is performed at two of the low-Btu facilities tested (Wellman-Galusha at Fort Snelling, and Foster-Wheeler/STOIC at UMD). As-received coal is crushed and sized on site at all of the medium-Btu facilities considered in this report. At the Lurgi-type (Kosovo), KRW PDU, and Koppers-Totzek (Modderfontein and Ptolemais) facilities, coal drying is performed. The entrained-bed gasifiers (Koppers-Totzek and Texaco) require more extensive preparation (crushing and pulverizing) to produce the finely divided coal feed used in these gasifiers.

A variety of methods are used to feed the prepared coal into the gasifiers. Lockhoppers are used with Wellman-Galusha, Riley, Foster-Wheeler/STOIC, Lurgi and KRW gasifiers. At the Chapman gasifier facility, coal is fed by means of a rotary feeding device known as a barrel valve. In the GKT gasifier, coal is augered out of a storage vessel and transported to the gasifier in a heated stream of steam and oxygen using a screw conveyor. The Texaco gasifier utilizes a slurry system in which pulverized coal is mixed with water, preheated, and pumped into the gasifier vessel.

Figures 5 through 7 summarize coal composition, gasifier feed rates, and reactant ratios for each of the gasification facilities. Flow rates are shown on a "per gasifier" basis to facilitate comparisons. The reactant ratios were calculated based on the reported feed rates. For the air-blown gasifiers, the oxygen to coal ratio was calculated based on an oxygen content of 23.1 percent by weight for air.

SUMMARY AND COMPARISON OF DOWNSTREAM PROCESSING OPERATIONS

Processing operations downstream of gasification are needed to perform various functions including:

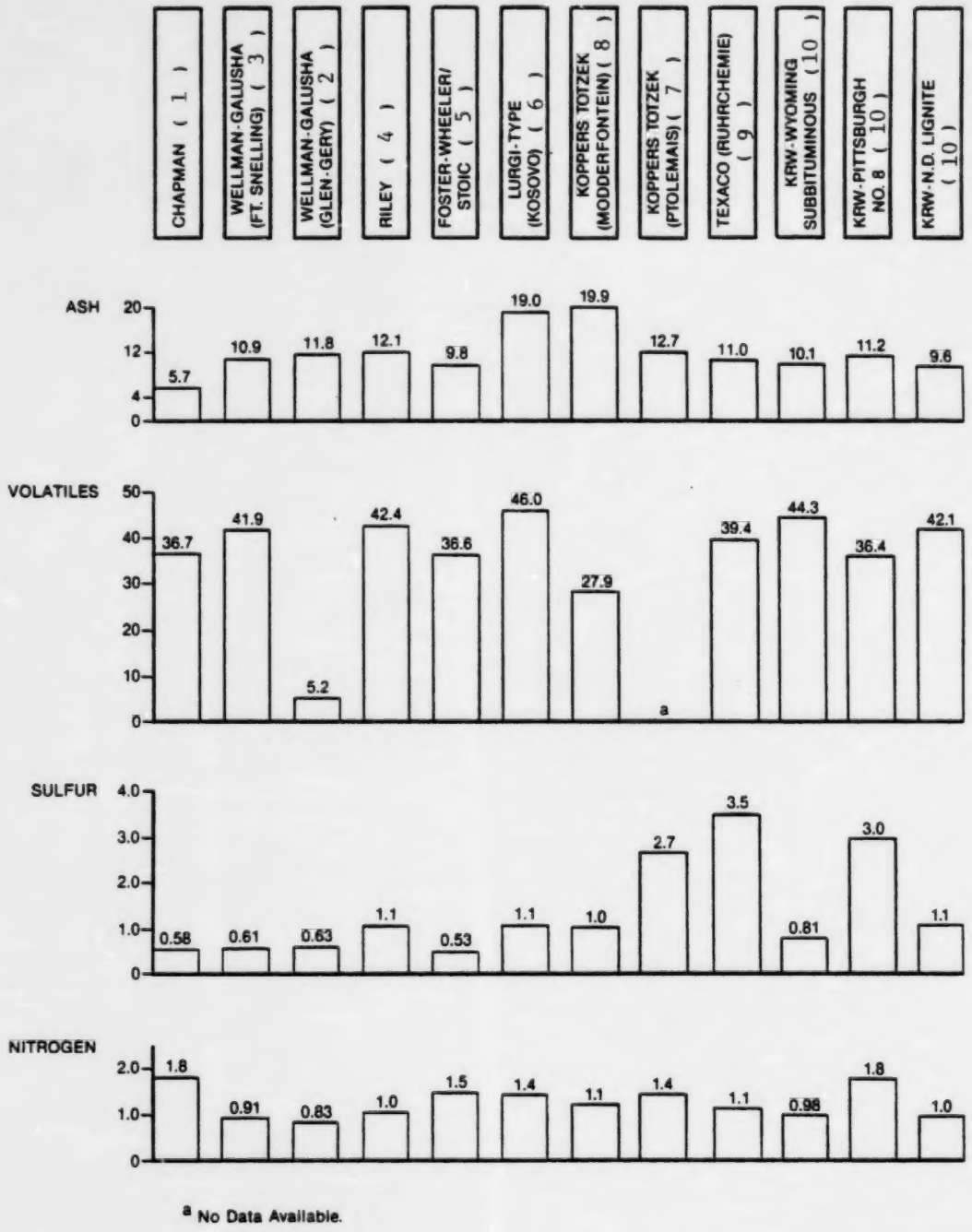
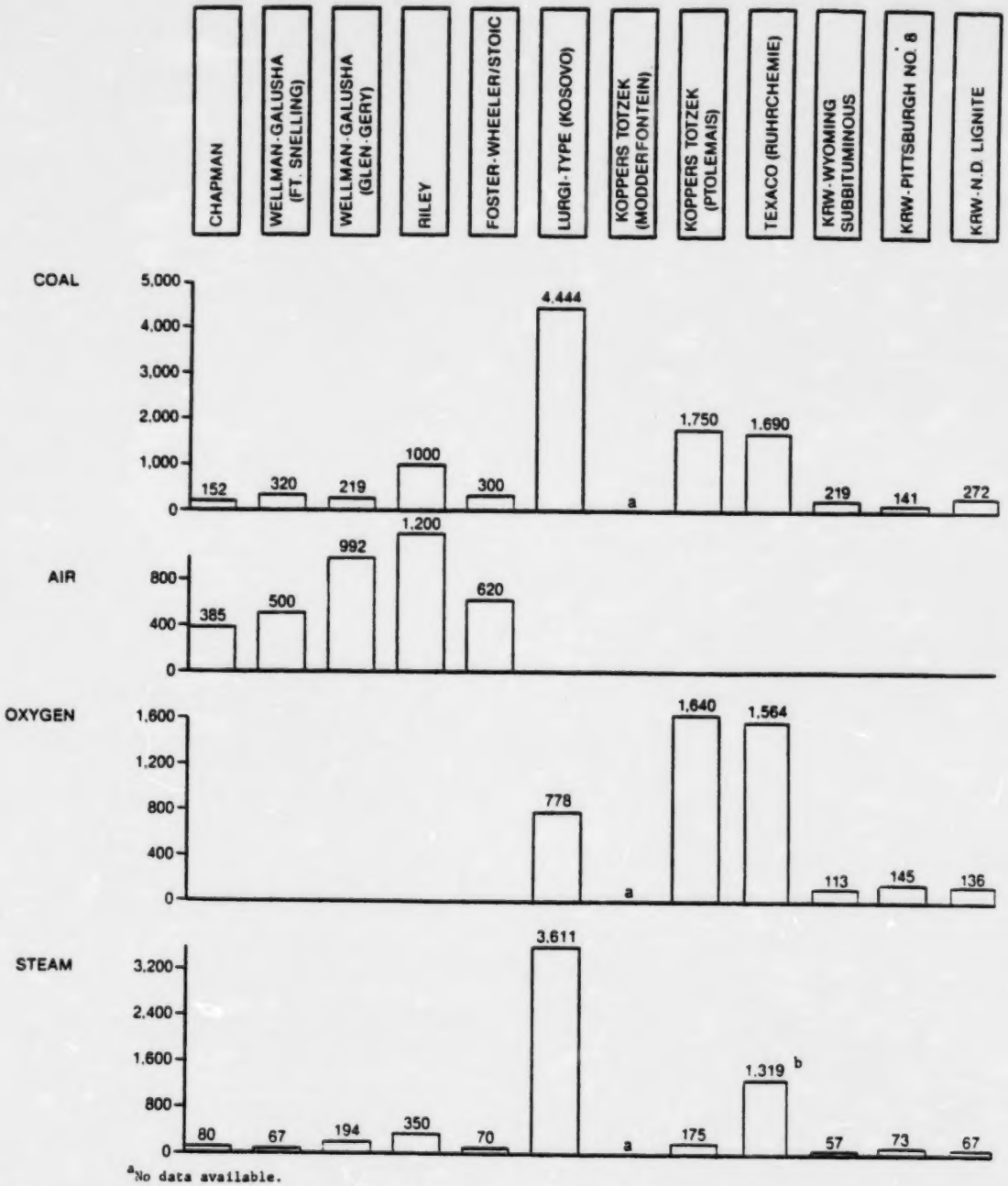


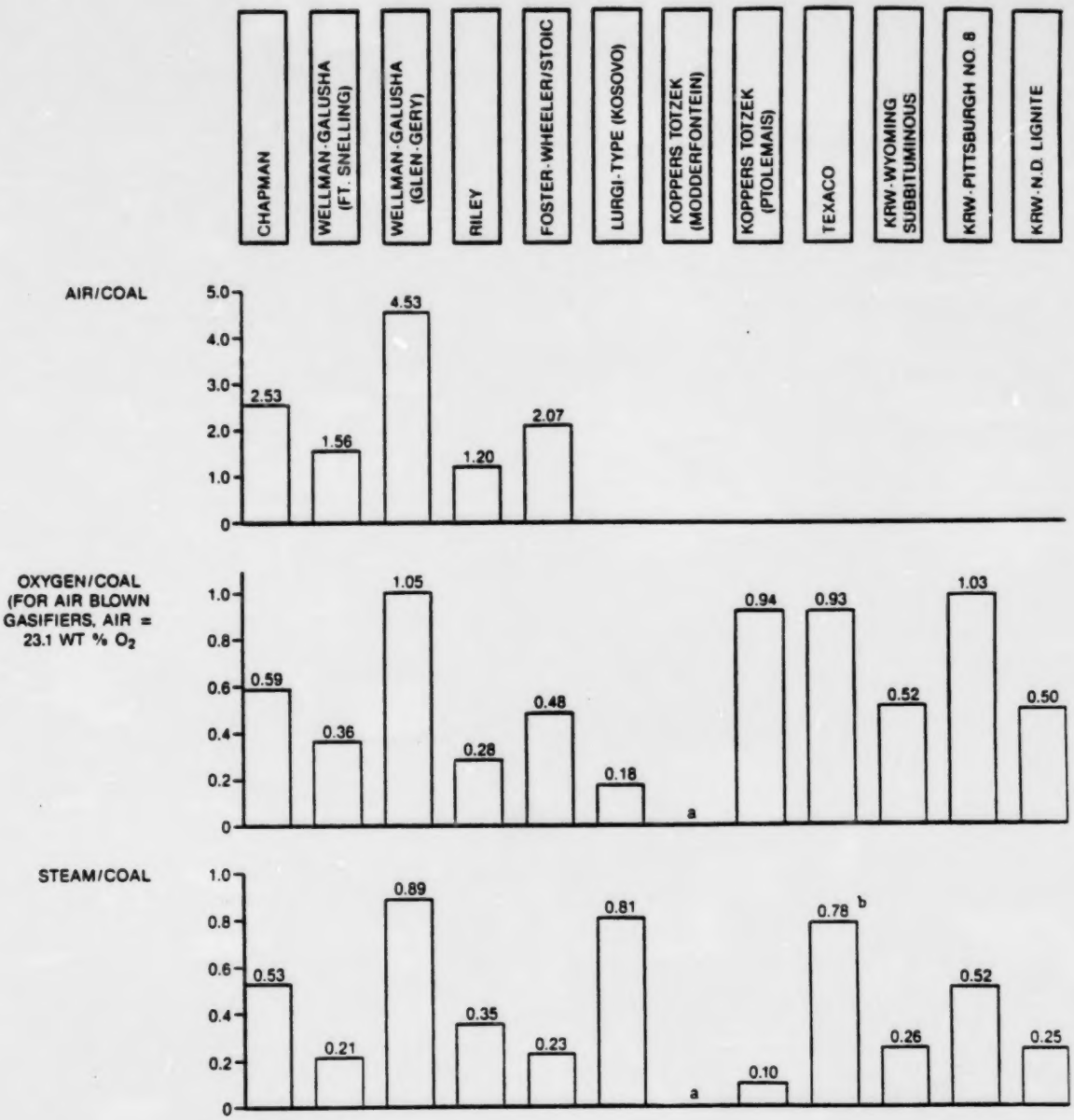
Figure 5. Comparative coal feedstock analyses, dry basis, wt. %.



[a]No data available.

[b]For the Texaco Gasifier Only, the Steam Flow Rate is Taken as the Fresh Makeup Slurry Water, Coal Moisture, and Water in Additive and Flocculant.

Figure 6. Comparative gasifier feed rates, g/sec-gasifier.



[a]No data available.

[b]For the Texaco Gasifier Only, the Steam Flow Rate is Taken as the Fresh Makeup Slurry Water, Coal Moisture, and Water in Additive and Flocculant.

Figure 7. Comparative gasifier feed ratios, kg/kg.

- Removal of entrained particulates (fly ash, tar, oil, etc.),
- Removal of gaseous contaminants (primarily sulfur and nitrogen species),
- Cooling of the raw product gas,
- Handling and disposal of solid wastes,
- Treatment and disposal of wastewater,
- Recovery of by-products (e.g., sulfur, ammonia, organics),
- Control of air pollutants, and
- Upgrading of the raw gas.

All of these processing operations are not present in all gasification facilities. Those found in the gasification facilities included in this report were shown in Table 1. Figures 8 through 17 are simplified block flow diagrams of these facilities. The major processing units and streams present in each of the facilities are shown, together with stream temperature data obtained at the time the facilities were characterized. Those streams for which composition and/or flow rate data were obtained are also indicated. These diagrams clearly show similarities and differences among the facilities.

In general, the low-Btu gasification facilities have much less extensive downstream processing than the larger, more complex medium-Btu facilities. In addition, since the emphasis at the KRW PDU is on gasifier development, limited gas cleaning is practical. In several of the low-Btu facilities, gas cleanup consists only of removing entrained particulates, typically by the use of cyclone separators. This is particularly true of the facilities which produce a hot fuel gas for direct combustion in a process

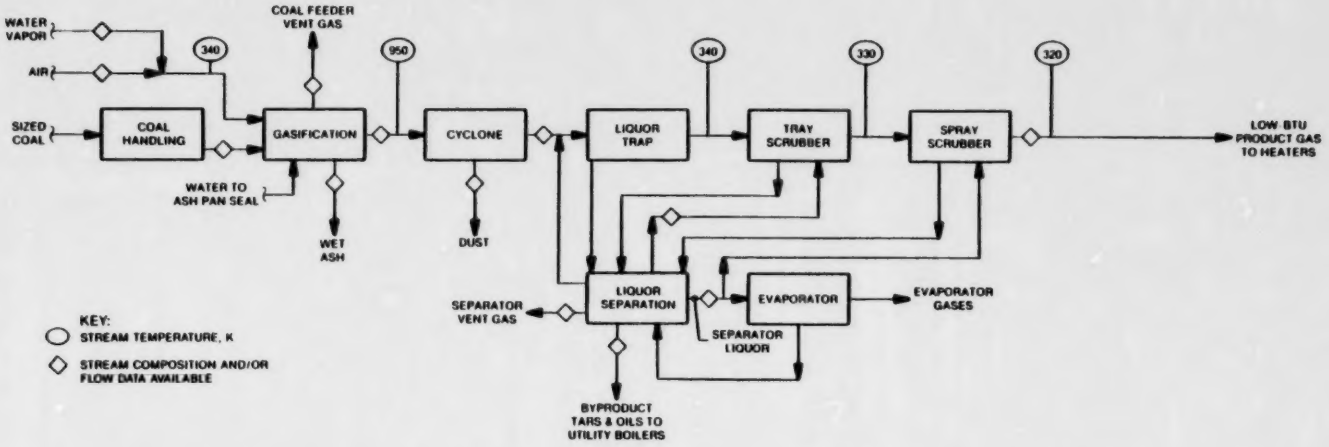


Figure 8. Simplified block flow diagram of Chapman gasifier.

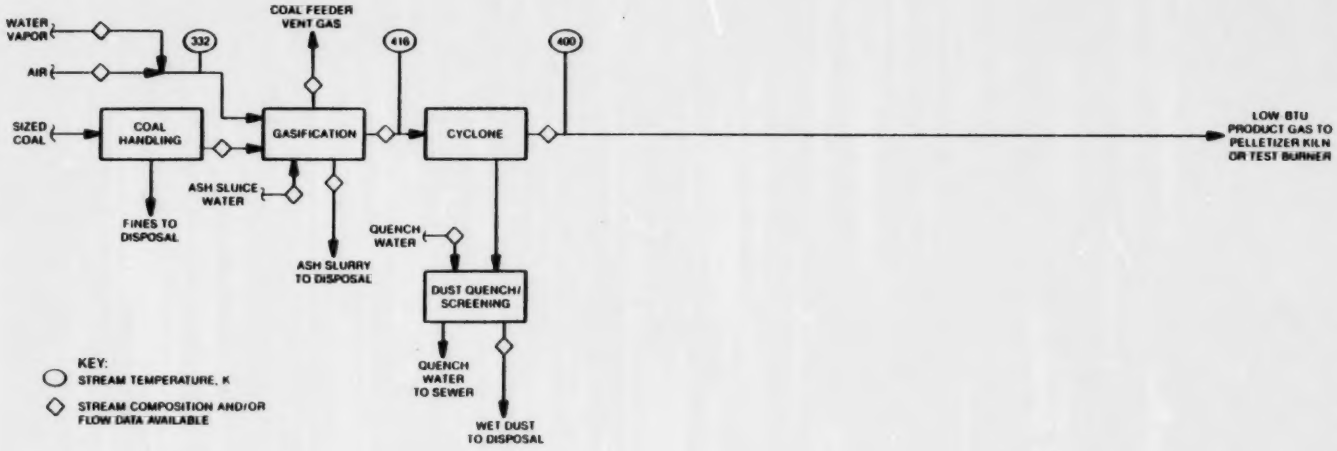


Figure 9. Simplified block flow diagram of Wellman-Galusha (Ft. Snelling) gasifier.

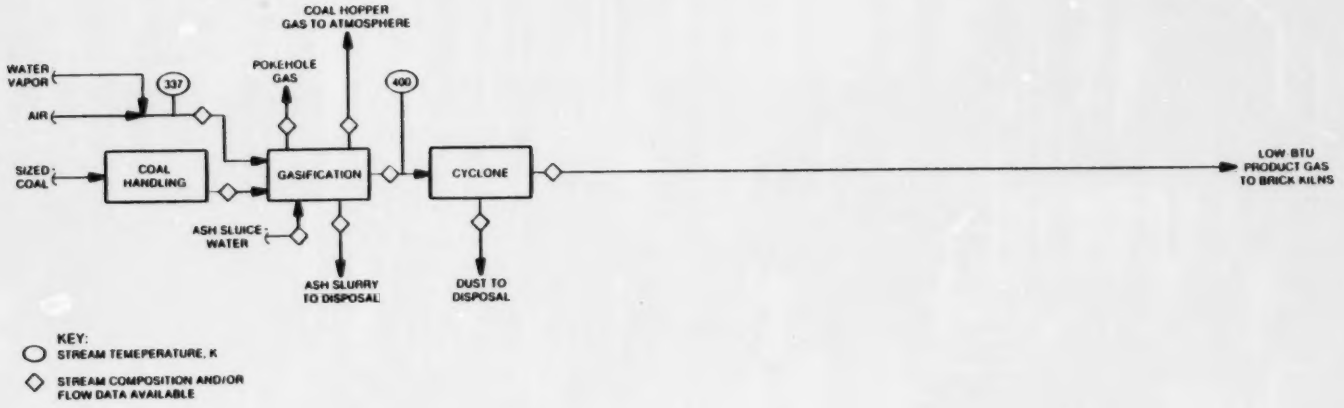


Figure 10. Simplified block flow diagram of Wellman-Galusha (Glen-Gery) gasifier.

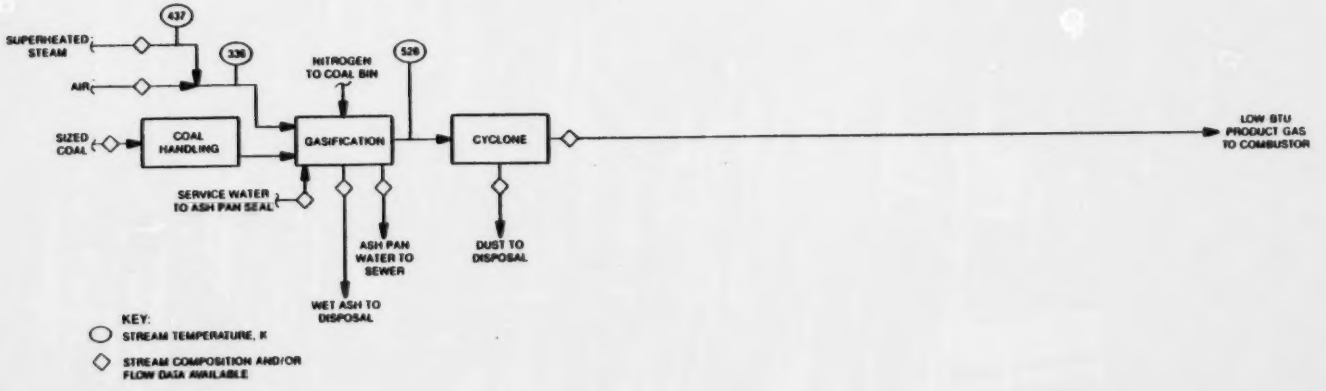


Figure 11. Simplified block flow diagram of Riley gasifier.

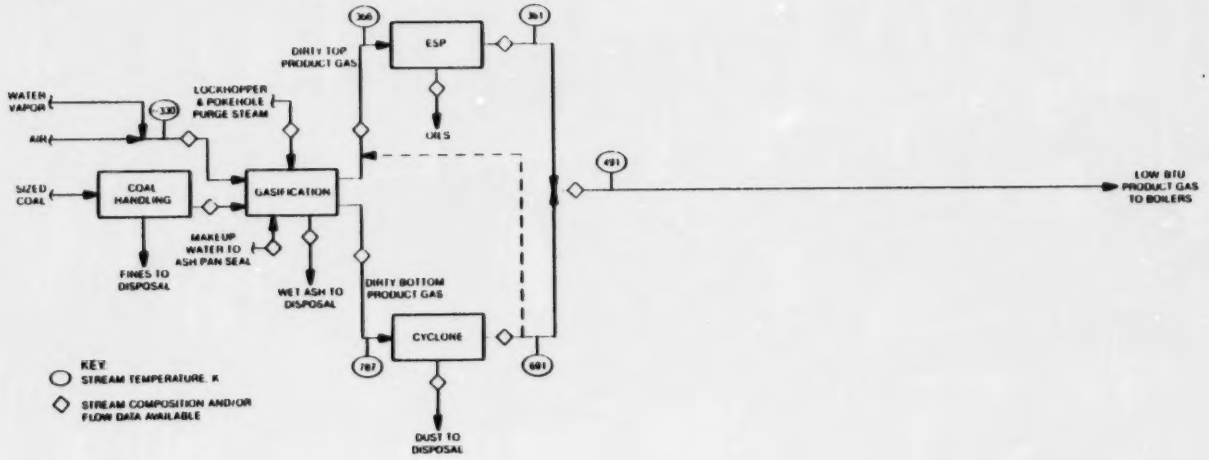


Figure 12. Simplified block flow diagram of Foster-Wheeler/STOIC gasifier.

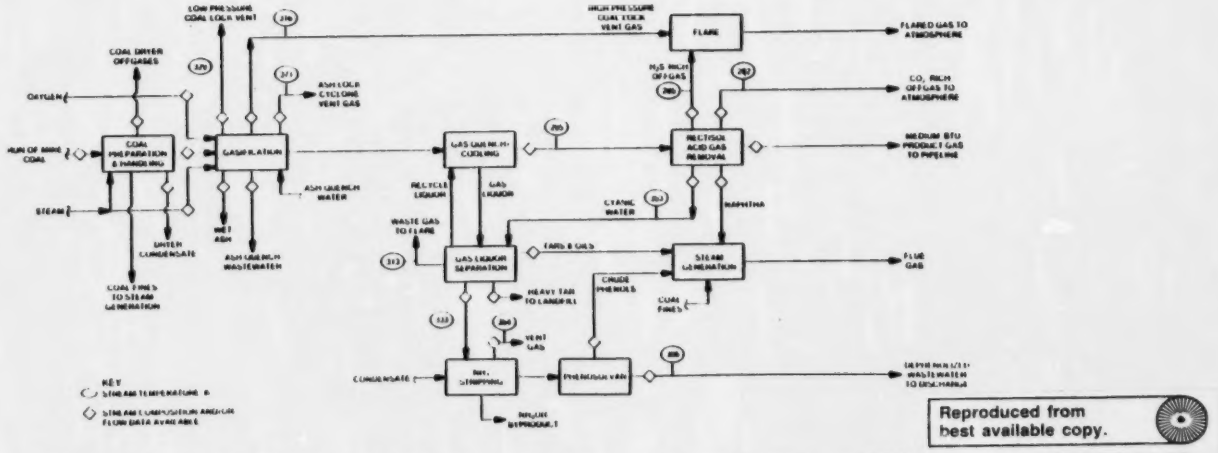


Figure 13. Simplified block flow diagram of Lurgi-type gasifier.

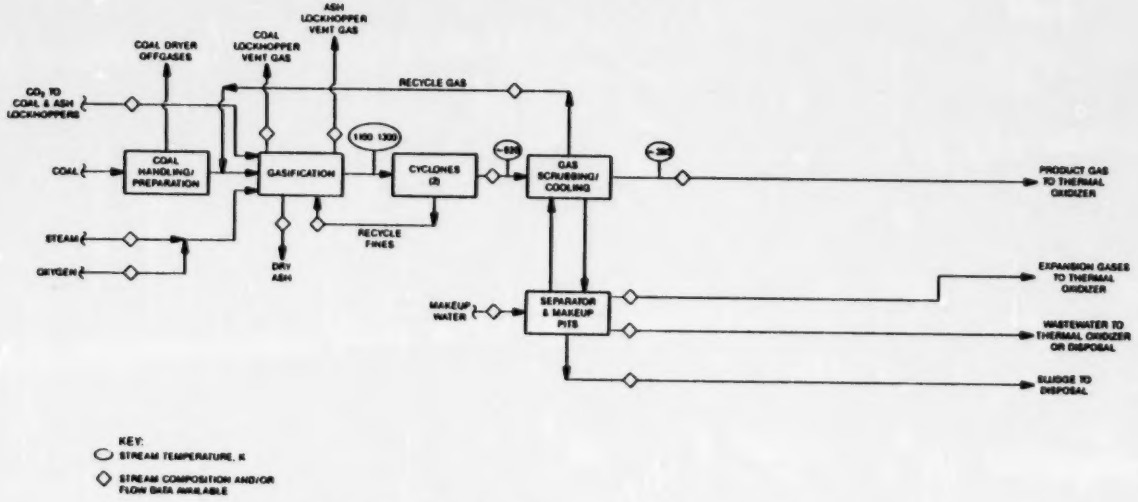


Figure 14. Simplified block flow diagram of KRW PDU gasifier.

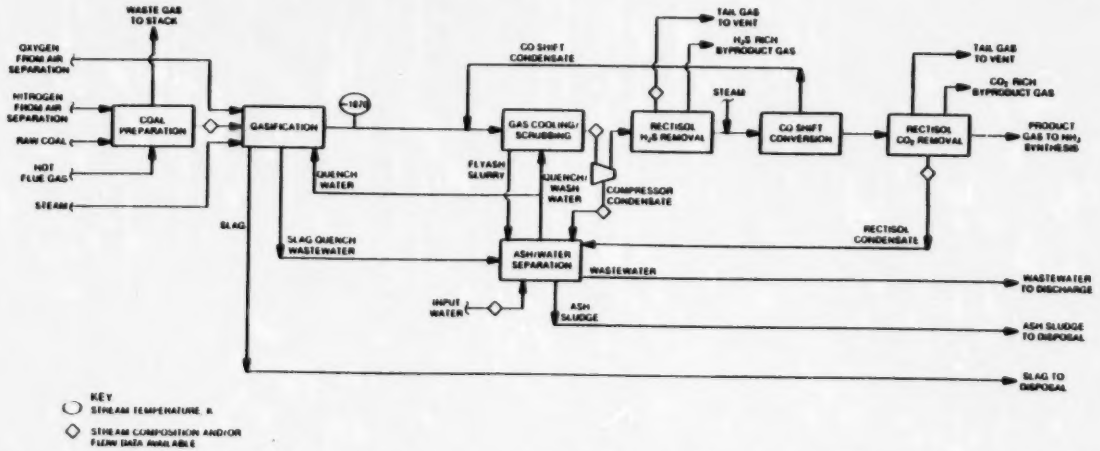


Figure 15. Simplified block flow diagram of Koppers-Totzek (Modderfontein) gasifier.

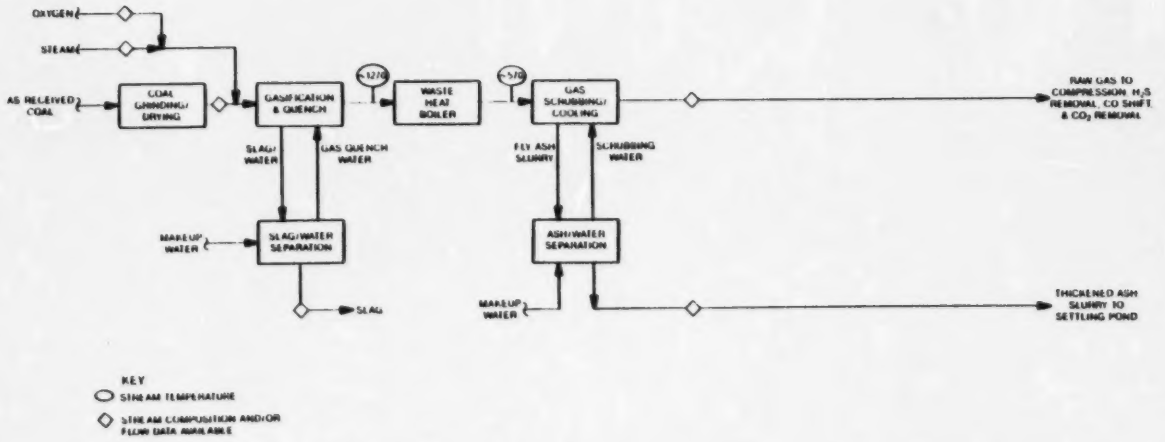


Figure 16. Simplified block flow diagram of Koppers-Totzek (Ptolemais) gasifier.

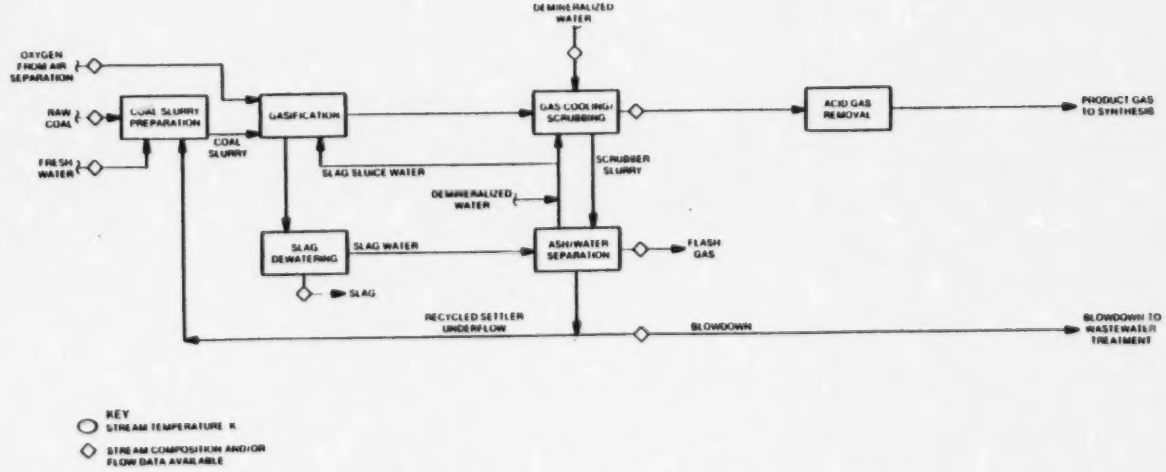


Figure 17. Simplified block flow diagram of Texaco/Ruhrchemie gasifier.

furnace. The Foster-Wheeler/STOIC facility (which features two-stage gasification) utilizes an electrostatic precipitator (ESP) to remove oil and tar particulates from the top gas and a cyclone to remove dust from the bottom gas. Of the low-Btu gasifiers tested, only the Chapman facility utilizes wet scrubbing and produces a cooled fuel gas, by-product tars and oils, and a process condensate (wastewater) stream. Some type of wet scrubbing is used in all of the medium-Btu facilities. None of the low-Btu facilities have acid gas removal systems; all of the commercial medium-Btu facilities have such units.

Ash/slag removal techniques also vary. All of the facilities except the KRW PDU use water to quench the hot ash/slag or to facilitate its removal from the gasifier vessel by sluicing. The pressurized gasifiers (Lurgi, KRW, and Texaco) all utilize lock hoppers to remove ash/slag. The others utilize ash plows, mechanical conveyors, or slide valves.

The downstream processing operations can significantly influence the fates of the various solid, liquid, and gaseous pollutants generated in the gasifier. Components originally found in the raw gas may be removed by these operations and distributed into a number of secondary solid, liquid, or gaseous streams. This distribution depends on the way in which these processes are linked together, how they are designed and operated, and on stream compositions.

Flow rate data for the major streams entering and leaving the downstream processing units for each of the facilities considered are summarized in Appendix A.

SECTION 4

SULFUR AND NITROGEN DISTRIBUTION SUMMARY

The majority of the total sulfur and nitrogen present in the coal is converted to gaseous species during the gasification process. Figure 18 summarizes the distribution of the total measured sulfur exiting the gasifier in the major process streams. The aqueous discharges from most of the smaller pilot-scale facilities were not accessible for accurate flow rate measurement. Therefore, although sulfur species (sulfate, sulfite, sulfide, and thiocyanate) were detected and quantified in these process streams, insufficient data are available to calculate outlet sulfur mass distributions including the aqueous outlet streams. Based on the good overall accountability of the coal sulfur, the process chemistry, and the very low contribution from the aqueous discharges which were measured at the Kosovo Lurgi-type gasifier and at the KRW-PDU, it is most unlikely that the availability of those data for all the gasification processes reviewed would appreciably alter the general trend of the distributions.

The figure shows that for the fixed-bed gasifiers, only the Chapman gasifier and the Riley gas producer had less than 80 percent of the outlet sulfur present in the crude product gas. The KRW-PDU had less than 80 percent of the outlet sulfur present in the crude product gas from bituminous coal and lignite gasification. However, in that process configuration, some raw product gas is recycled to pressurize/fluidize the feed coal. The sulfur

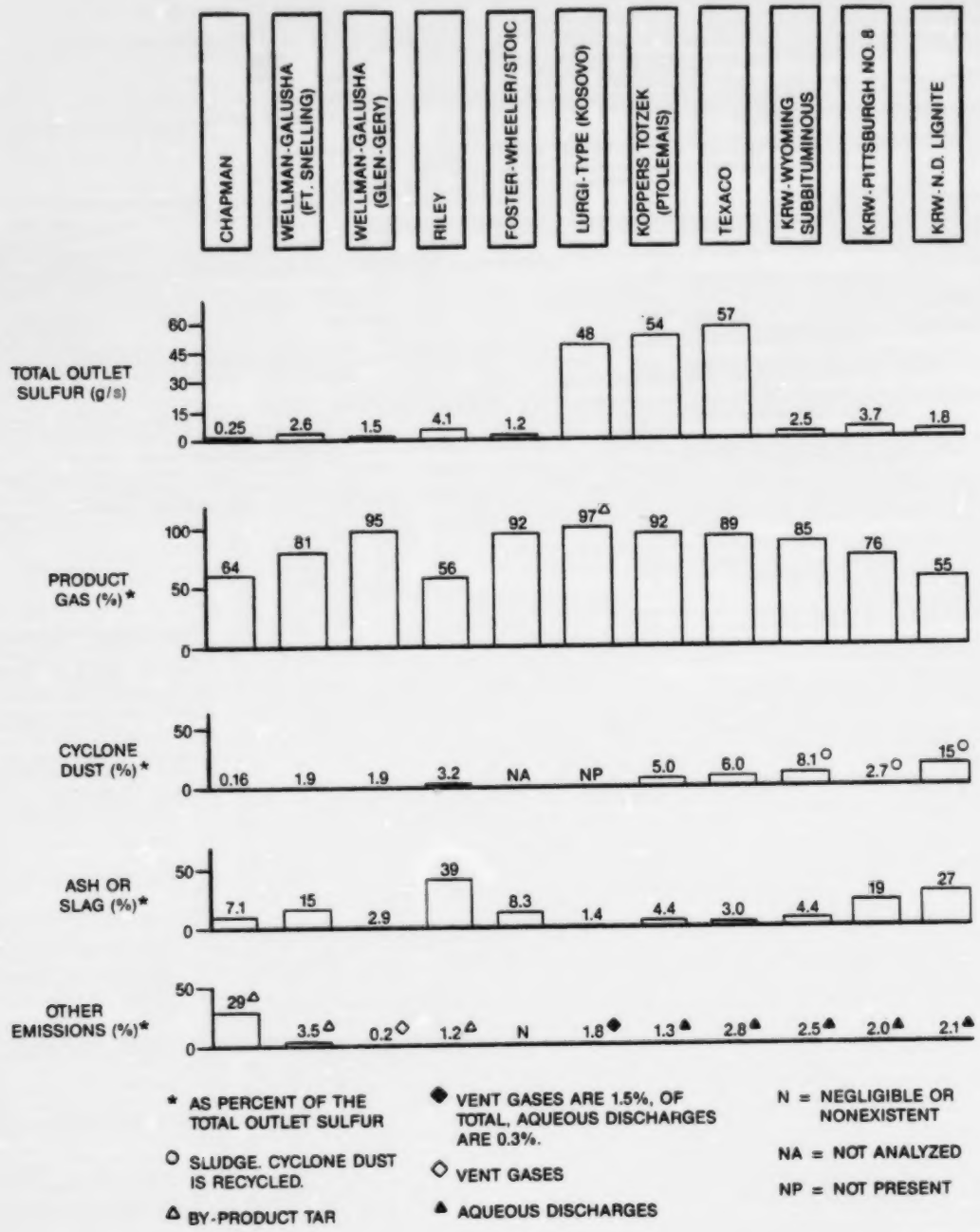

CHAPMAN
WELLMAN-GALUSHA (FT. SNELLING)
WELLMAN-GALUSHA (GLEN-GERY)
RILEY
FOSTER-WHEELER/STOIC
LURGI-TYPE (KOSOVO)
KOPPERS TOTZEK (PTOLEMAIS)
TEXACO
KRW-WYOMING SUBBITUMINOUS
KRW-PITTSBURGH NO. 8
KRW-N.D. LIGNITE
TOTAL OUTLET SULFUR (g/s)
0.25 2.6 1.5 4.1 1.2 48 54 57 2.5 3.7 1.8
PRODUCT GAS (%)*
64 81 95 56 92 97△ 92 89 85 76 55
CYCLONE DUST (%)*
0.16 1.9 1.9 3.2 NA NP 5.0 6.0 8.1○ 2.7○ 15○
ASH OR SLAG (%)*
7.1 15 2.9 39 8.3 1.4 4.4 3.0 4.4 19 27
OTHER EMISSIONS (%)*
29△ 3.5△ 0.2◇ 1.2△ N 1.8◆ 1.3▲ 2.8▲ 2.5▲ 2.0▲ 2.1▲
* AS PERCENT OF THE TOTAL OUTLET SULFUR
○ SLUDGE. CYCLONE DUST IS RECYCLED.
△ BY-PRODUCT TAR
◆ VENT GASES ARE 1.5%, OF TOTAL, AQUEOUS DISCHARGES ARE 0.3%.
◇ VENT GASES
▲ AQUEOUS DISCHARGES
N = NEGLIGIBLE OR NONEXISTENT
NA = NOT ANALYZED
NP = NOT PRESENT

Figure 18. Sulfur distribution among outlet streams.

in this recycle gas was excluded in the raw product gas calculations. Therefore, some greater uncertainty may have been introduced by this method of calculating the mass flow of sulfur in the raw product gas. Comparing the Chapman to the Lurgi-type (Kosovo) gasifier, both of which are tar producers, the sulfur distribution between the gaseous and condensible phases is distinctly different. For the Lurgi-type gasifier, 97 percent of the total outlet sulfur was contained in the crude product gas. Data from the Lurgi-type facility after tar/oil removal from the crude product gas shows that only approximately one to two percent of the raw gas sulfur is in the condensible tars and oils. The Chapman tar/oil stream, however, contained 28 percent of the total outlet sulfur.

The Riley gas producer which was operated on North Dakota lignite is an anomaly in the tar-producer group. The outlet sulfur is distributed between the crude product gas and the gasifier ash at almost a 3:2 ratio. The Wellman-Galusha gasifier at Fort Snelling was operated on North Dakota lignite also, and that sulfur distribution also shows a moderately low gas to solid ratio (approximately 5:1). The outlet sulfur distribution of the non-tar producing KRW-PDU is similar (crude gas to slag of 2:1) to the Riley gas producer for the gasification of North Dakota lignite. Whether this distribution pattern is directly related to the feedstock is not clear. The KRW-Pittsburgh #8 test sulfur distribution also has a low gas to solid ratio (4:1) but a 20:1 gas to solid sulfur ratio for the Wyoming sub-bituminous test. The remaining fixed-bed gasifiers have the outlet sulfur concentrated in the product gases, a small but significant amount in the ash (3-8 percent), and approximately two percent in the raw gas particulates (cyclone dust).

The distribution of the total outlet nitrogen generally parallels the outlet sulfur distribution with the majority of the nitrogen exiting in the gas streams as shown in Figure 19. Again, the Chapman gasifier does not follow the trend. Excluding the diluent nitrogen, 82 percent of the outlet nitrogen leaves the Chapman gasification process in the tar/oil. The Wellman-Galusha gasifier at Fort Snelling also had a significant amount of the outlet

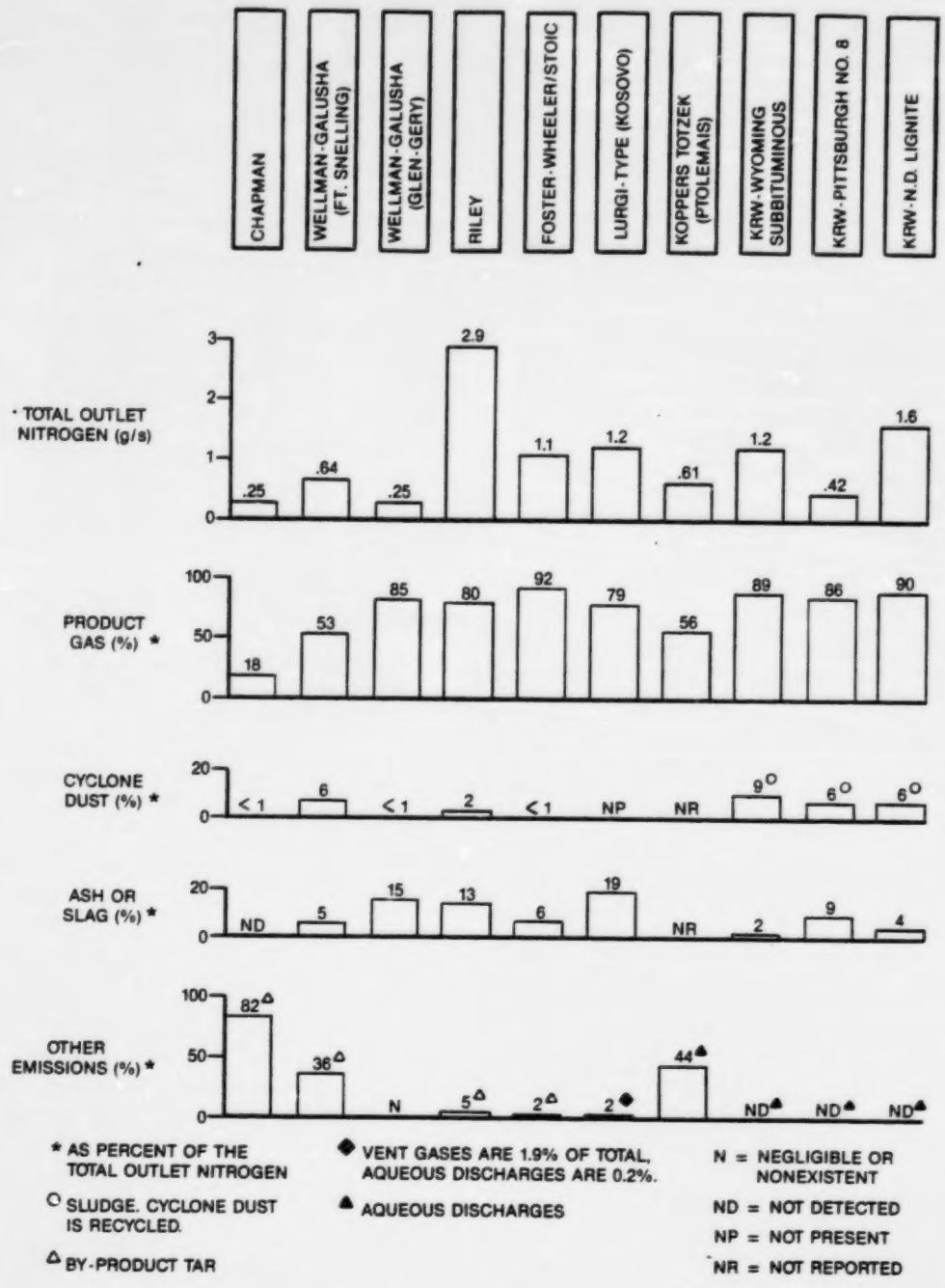


Figure 19. Nitrogen distribution among outlet streams (excluding N_2).

nitrogen (36 percent) present in the tar/oil. Of the other gasification processes for which outlet stream nitrogen data were available, over 80 percent of the nitrogen is present in the gas phase with the ash and cyclone dust containing the remaining outlet nitrogen.

VAPOR PHASE DISTRIBUTIONS

The product gas contained the majority of the sulfur leaving the gasification process and the majority of the product gas sulfur was in the form of hydrogen sulfide. The most consistent trend apparent in the overall gasification distributions reviewed here is that of the volatile sulfur species. Between 82 and 94 percent of the vapor phase sulfur from eight of the gasification processes reviewed is present as hydrogen sulfide. Volatile sulfur speciation data was not available for the Texaco gasifier at the Ruhrchemie facility. Since species of interest and speciation techniques varied during the five-year period when these data were collected, the occurrence and distribution of the minor volatile sulfur species is less well-defined.

One to three percent of the measured vapor phase sulfur was sulfur dioxide in the Chapman and both Wellman-Galusha gasifiers. This level of oxidized sulfur in the product gas is an indicator of excessive combustion (incomplete gasification) within these fixed-bed gasifiers probably due to channels forming in the bed of the gasifier creating localized oxygen-rich combustion zones. The minor reduced sulfur species, carbonyl sulfide, methyl mercaptan, ethyl mercaptan, and carbon disulfide generally were present at detectable levels (where those analyses were conducted) with the exception of raw gas from the KRW-PDU as seen in Figure 20 which summarizes the vapor phase sulfur distributions. The percentage of the product gas sulfur present as carbonyl sulfide is not very high, averaging 10 percent over these processes. However, carbonyl sulfide is not easily removed from the product gas by some sulfur removal/recovery processes. Therefore, the mass of reduced sulfur which can potentially escape these removal processes could be significant if the carbonyl sulfide is not converted to hydrogen sulfide. Of

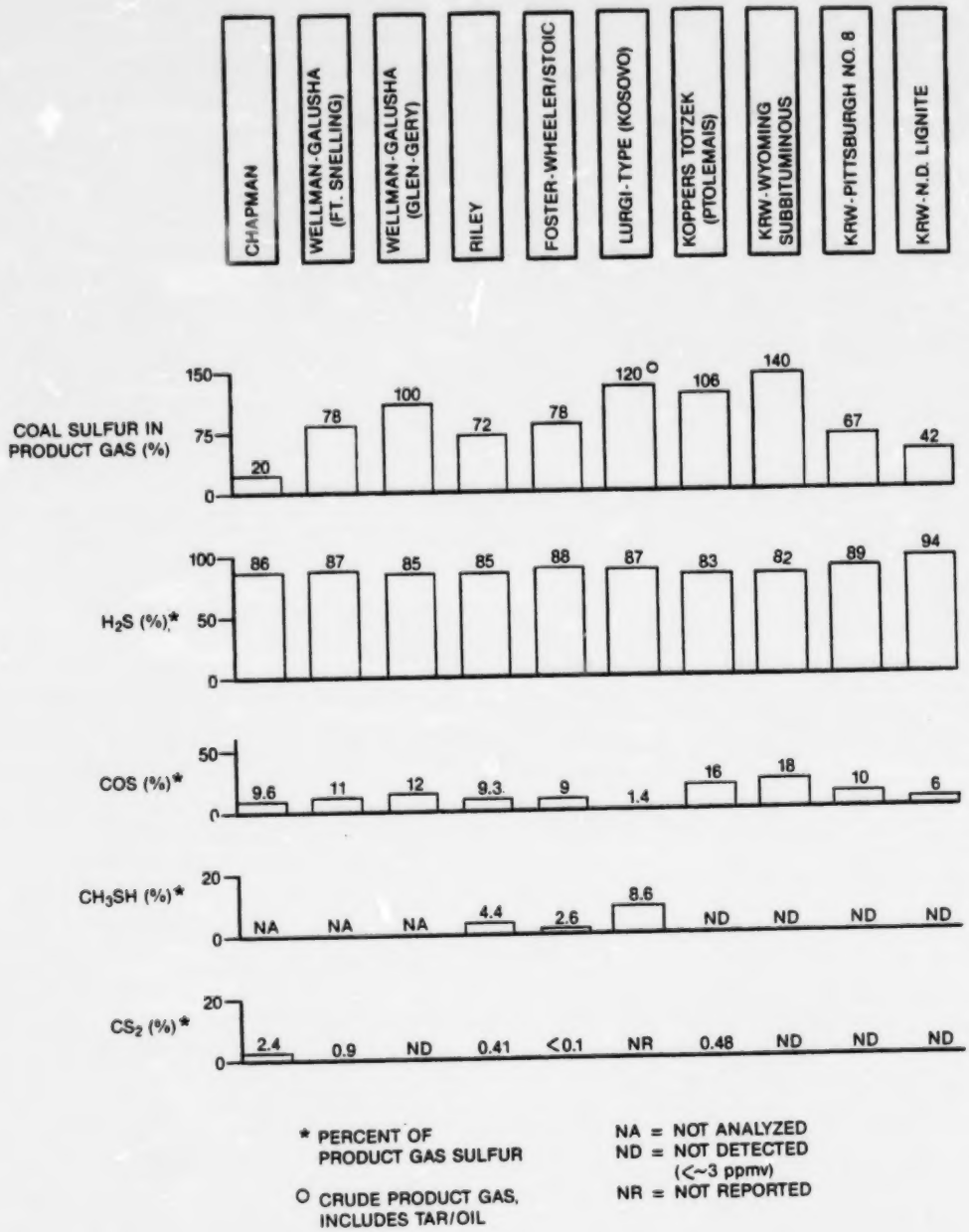


Figure 20. Distribution of vapor phase sulfur species.

the facilities reviewed, the Lurgi-type (Kosovo) and the Koppers-Totzek had sulfur removal processes operating.

At the Lurgi-type plant, a Rectisol (chilled methanol) unit was used to remove acid gases from the crude product gas. Only traces of reduced sulfur species (H_2S, COS, CH_3SH, C_2H_5SH) were found in the clean product gas (non-detectable at 2 ppmv). The sulfur compounds exited the Rectisol unit in one of two streams as a result of the two-stage solvent flashing and stripping configuration employed there. The hydrogen sulfide-rich waste gas contained over 99 percent of the total measured volatile sulfur. The carbon dioxide-rich waste gas contained measurable amounts of reduced species. The CO_2-rich waste gas contained 20-90 ppmv hydrogen sulfide, variable amounts of carbonyl sulfide ranging from 1-60 ppmv, 8-10 ppmv methyl mercaptan, and 3-6 ppmv ethyl mercaptan. A Rectisol unit was used for acid gas removal at the Koppers-Totzek facility in Modderfontein also. Data on volatile sulfur species are available only for the carbon dioxide-rich waste gas. Less than 5 ppmv of any volatile sulfur compound was detected. At the Koppers-Totzek facility in Ptolemais, 4 ppmv of hydrogen sulfide were detected in the carbon dioxide-rich waste gas from the Rectisol unit. No volatile sulfur species were reported as present in the cleaned synthesis gas. The hydrogen sulfide-rich stream from the Rectisol unit (Claus process feed gas) was 22.21 percent hydrogen sulfide, 2.47 percent carbonyl sulfide, 0.09 percent carbon disulfide and 0.19 percent cyanide (reported as HCN).

Direct combustion tests were run at the Wellman-Galusha gasifiers, the Riley gas producer and the Foster-Wheeler/STOIC facility. The fate of the vapor phase sulfur species was determined in those tests. In the low-Btu gas combustion test firing the product gas from the Foster-Wheeler/STOIC gasifier in a conventional boiler complete conversion to sulfur dioxide was achieved. The combustion gases from the smaller-scale combustion tests occasionally contained traces of reduced sulfur species.

The nitrogen species distributions in the raw product gases are very similar for the four low-Btu processes for which data are available. Ammonia

accounts for 81 to 87 percent of the vapor phase nitrogen (excluding N_2) with the remaining measured nitrogen present as cyanide. No vapor phase volatile amines or other low molecular weight organo-nitrogen species determinations were reported for these processes. Figure 21 presents a summary of these data and also shows the vapor phase inorganic nitrogen distribution in the product gases from the Lurgi-type gasifier, the Koppers-Totzek gasifiers at Modderfontein and Ptolemais, and the KRW gasifier. The product gases at both the Kosovo and Koppers-Totzek plants undergo an immediate scrub/quench which removes the more soluble ammonia from the hot gases more readily than the cyanide. Therefore, the data show low concentrations of vapor phase ammonia in the scrubbed gases. The unquenched gases analyzed from the other processes show a distribution of nitrogen species which are unaltered by aqueous scrubbing; however, similar samples were not obtained at the Lurgi-type or Koppers-Totzek facilities.

At the KRW-PDU, the product gas was analyzed prior to quench/cooling and after the quench/cooling. Those data from the bituminous coal test show no removal of vapor phase nitrogen species during the primary quench (gas to liquid ratio about 1.7) which lowers the product gas temperature from roughly 650°C to 160°C. During the lignite test, 40 percent of the ammonia and 25 percent of the cyanide were removed during this primary quench. Thiocyanate apparently followed the behavior of the volatile sulfur species across the primary quench since no appreciable decrease in concentration was measured. The subsequent quench/cooler reduces the product gas temperature to 120°C and effectively removed the ammonia to less than 1 to 2 percent of the raw gas levels for all three tests. Ammonia was not above the detection limits of 3 to 4 ppmv during any of the tests after the final quench/cooler which lowers the product gas to about 40°C. About 40 to 50 percent of the cyanide was removed by the time the product gas exited the second quench cooler. Final cooling brought the cyanide to about 10 percent of the initial levels and the thiocyanate to roughly 20 percent of the initial levels.

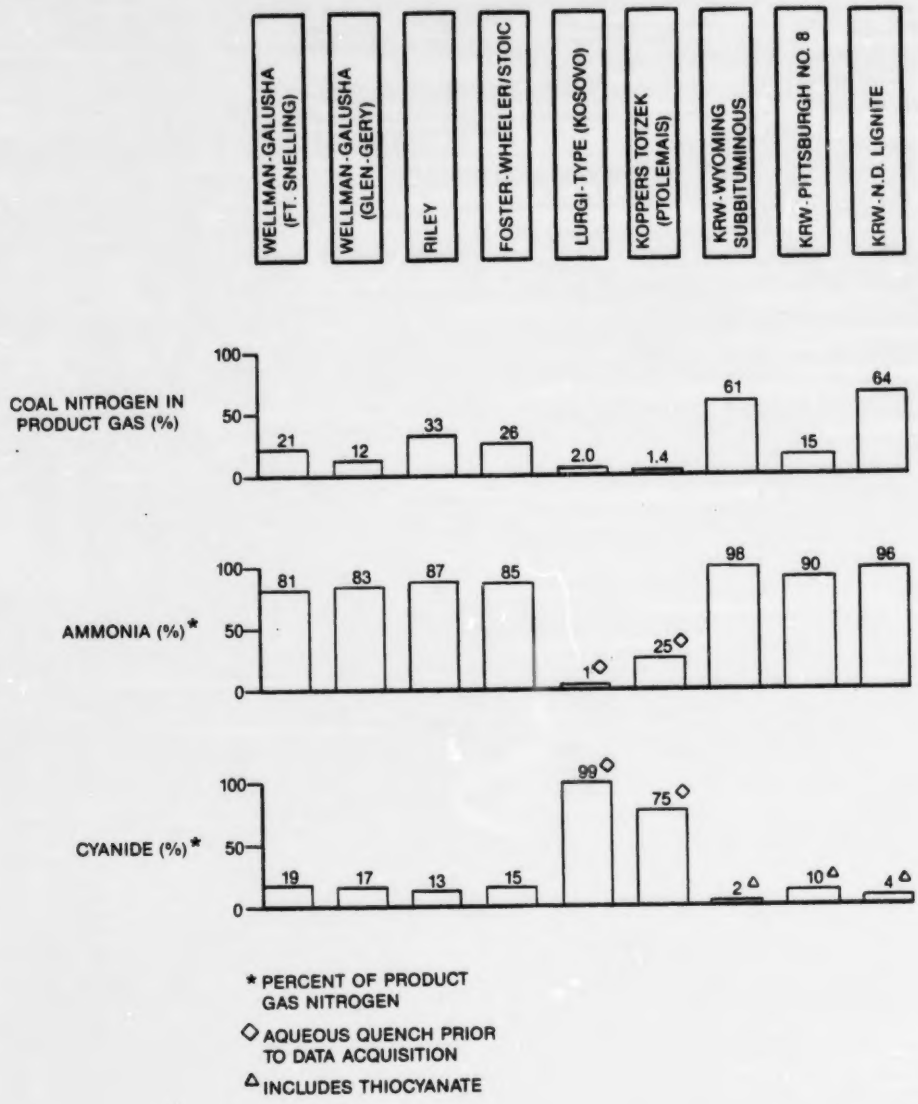


Figure 21. Distribution of vapor phase nitrogen species.

AQUEOUS SPECIES

Only minimal amounts of the coal sulfur exit the gasifier module in the process water. This was seen in the total sulfur accountability calculations summarized previously in Figure 1 which included few aqueous discharges from the gasifiers, yet most showed good total sulfur reconciliation. Removal of soluble sulfur species is often accomplished by coagulation/precipitation processes which can be very efficient. The major aqueous discharge from the air-blown gasifiers without gas quench/scrubbing is the ash or slag quenching and sluicing water which contains sulfate as the predominant sulfur species. The aqueous sulfur species distributions are summarized in Figure 22 for those processes with ash quench/sluice waters.

Sulfite data were not available for several of the processes. The Lurgi-type ash water was analyzed for sulfite and less than 1 mg/L was found. Sulfide levels were consistently below three percent of the aqueous sulfur. The sulfide concentrations in the ash waters varied from approximately 50 mg/L to less than 1 mg/L.

The distribution seen in the Foster-Wheeler/STOIC ash quench/sluice water was anomalous. That aqueous discharge contained moderately low levels of sulfur relative to the other fixed-bed processes and the aqueous species were distributed approximately 3:4:2 among sulfate, sulfite, and sulfide. Data are not available to clarify this anomaly. Oxidation of sulfide and sulfite to sulfate can occur in these aqueous streams. The oxidation reactions are probably enhanced by the ash minerals which are available in the streams. It may be the case that the aqueous sulfur species distributions of the fixed-bed gasifiers were similar to those of the Foster-Wheeler/STOIC at the time of contact with the ash, but that oxidation to sulfate proceeded more rapidly in the other gasifier streams. An alternative hypothesis is that the Foster-Wheeler/STOIC ash contained much higher levels of sulfite and sulfide than the ashes from other processes and that the ash quench/sluice water composition reflects aggressive initial leaching of the solid.

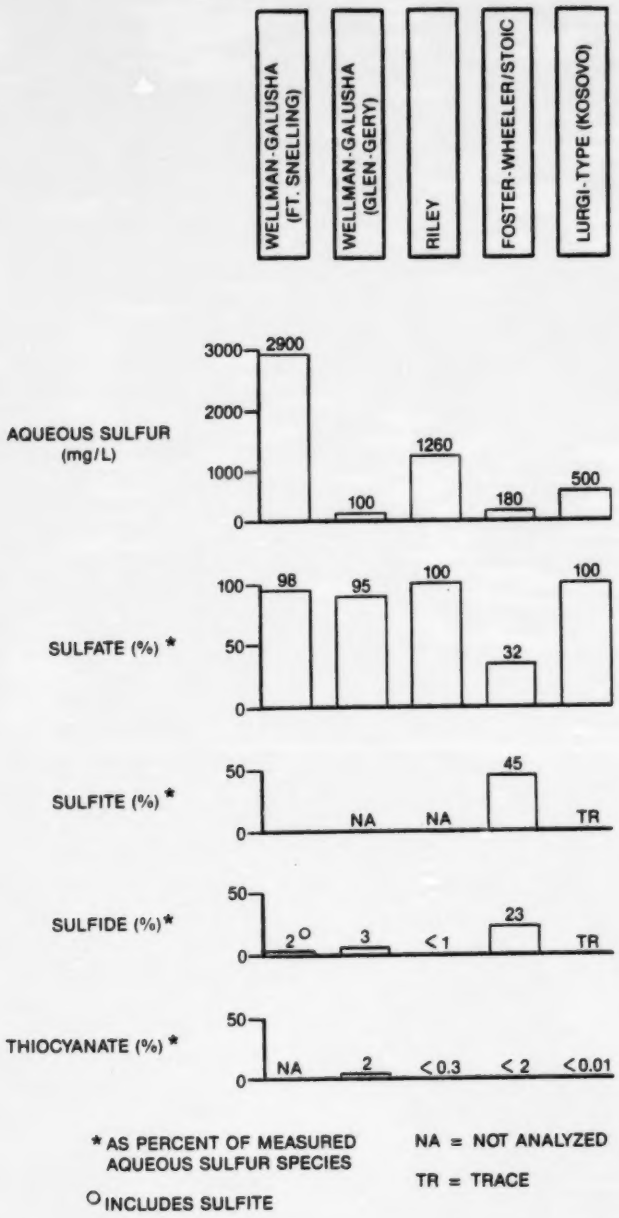


Figure 22. Distribution of sulfur species in aqueous streams that contact ash or slag.

The soluble sulfur species distributions for some aqueous process streams that do not contact ash or slag are given in Figure 23. The settler underflow from the Texaco process contacts the entrained gas particles. The Koppers-Totzek (Ptolemais) wash water to clarifier, the Wellman-Galusha (Fort Snelling) cyclone quench water and the KRW PDU wastewater blowdown also have contacted the entrained gas particles. For these streams, sulfate is still the predominant species. In contrast to the ash waters, the distribution of the other soluble sulfur species is higher relative to the sulfate levels.

Distributions for the aqueous nitrogen species become somewhat less consistent. Figure 24 summarizes the data for the nitrogen components identified in the ash sluice/quench discharge from the gasifiers. For the ash waters, nitrate/nitrite are the dominant species. The preponderance of the oxidized species parallels the sulfur distribution for the ash waters. The data from the Wellman-Galusha facility at Fort Snelling show a predominance of ammonia, a significant percentage of nitrate, and no detectable cyanide in the ash sluice/quench water. The water used to quench/sluice the raw gas cyclone dust at the same facility shows no oxidized nitrogen species but ammonia and a significant percentage of cyanide. Figure 25 shows the nitrogen species distributions for the waters which do not contact ash or slag. In these streams, ammonia clearly predominates. The cyanide and thiocyanate are roughly equivalent to each other and each is usually less than five percent of the total soluble nitrogen.

SOLID STREAMS

Little data are available on the species compositions of the sulfur or nitrogen contained in the gasifier ash or overhead particulates. In the overall material distributions (Figures 18 and 19), the ash/slag and cyclone dust each generally accounted for less than ten percent of the total outlet nitrogen and the total outlet sulfur. Variability for the outlet sulfur was rather broad as the ash or slag accounted for a range from less than two percent to almost 40 percent of the outlet sulfur.

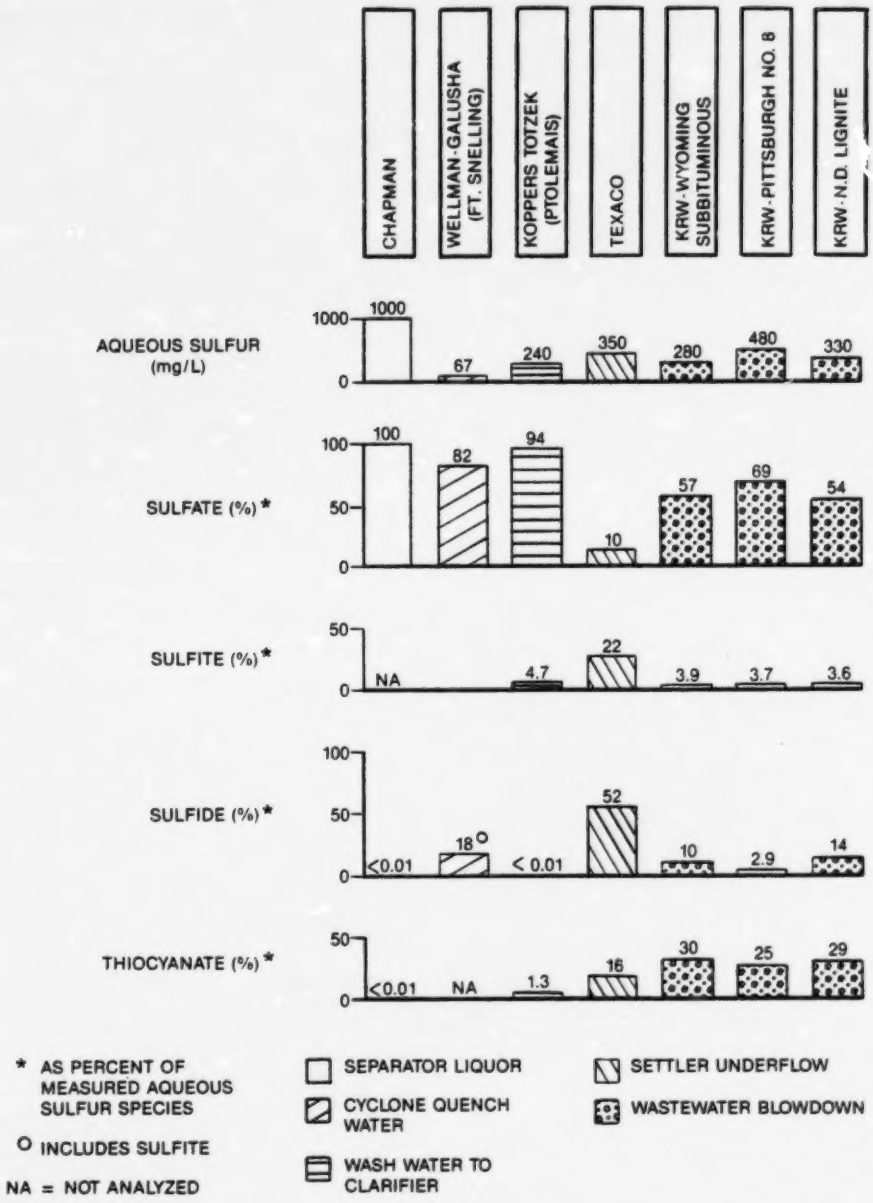


Figure 23. Distribution of sulfur species in aqueous streams.

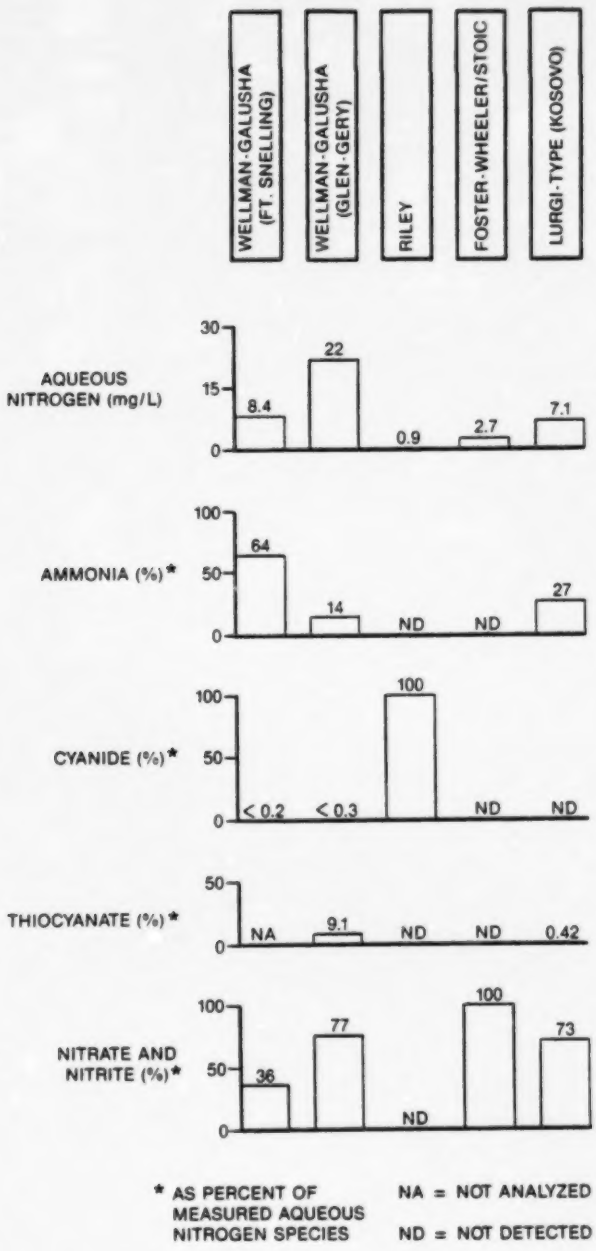


Figure 24. Distribution of nitrogen species in aqueous streams that contact ash or slag.

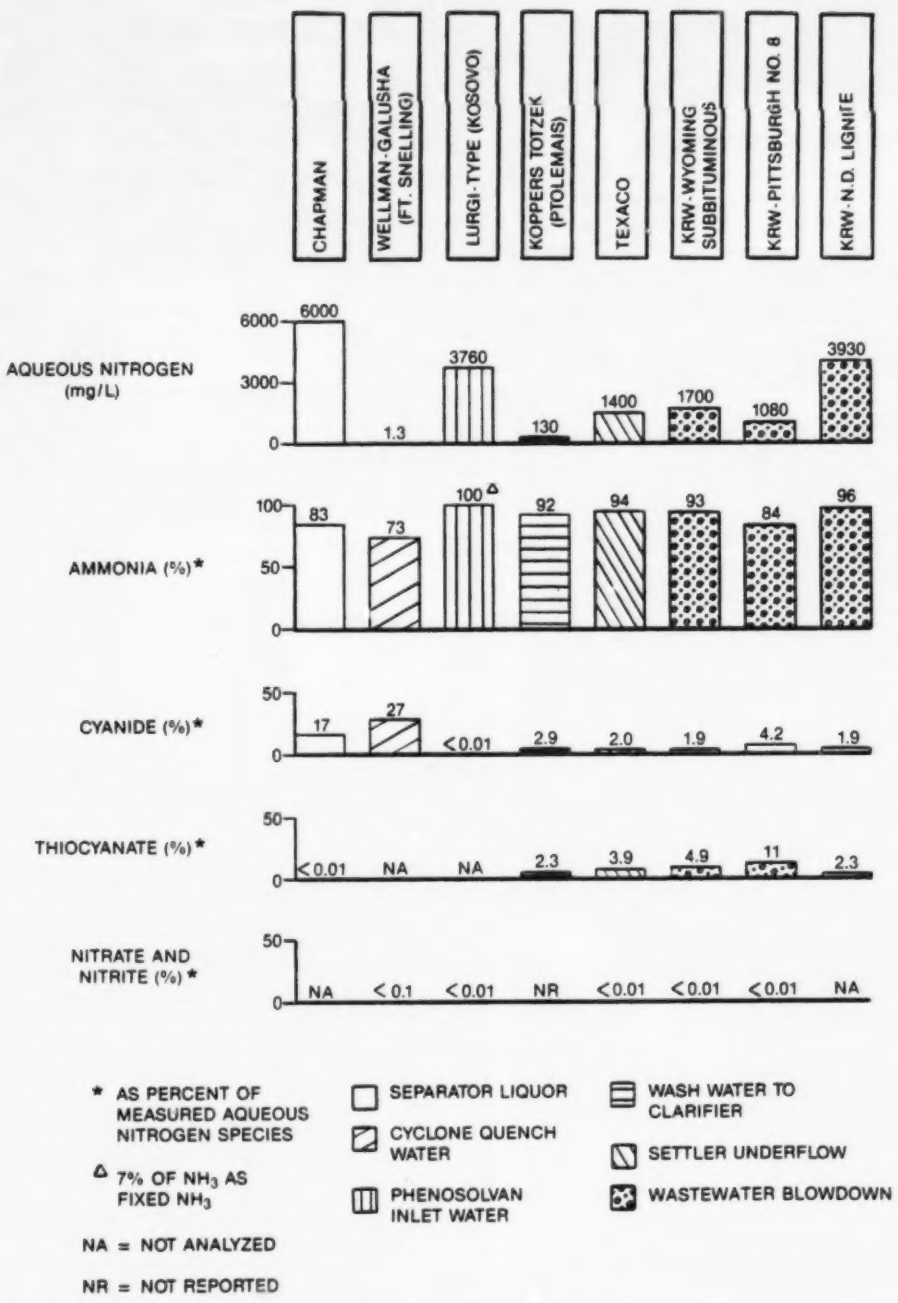


Figure 25. Distribution of nitrogen species in aqueous streams.

The sulfur distribution data for the process solids is given in Figure 26. The ash/slag usually contains over 70 percent of the sulfur leaving the process with the solids. The most striking anomaly in the solid sulfur distribution data are the outlet solids from the Koppers-Totzek (Ptolemais) facility. The slag accounts for only eight percent of the sulfur in the solids; the remaining 92 percent is contained in the solids removed from the process gas in the quench/wash water. This is broadly analogous to the data from two tests at the KRW PDU. The sludge which accumulates in the separator pit is the solids removed from the gas during the quench/cooling. The sludge contained 65 percent of the sulfur in the solids for the bituminous coal test and 36 percent during the lignite test. Of the atmospheric pressure gasifiers, only the Wellman-Galusha at Glen-Gery had a similar percentage of the outlet solids sulfur present in the cyclone dust. The occurrence of sulfur in the ash/slag and entrained particles is likely to follow a trend established by the carbon conversion for each process test. Processes or individual coal tests with higher carbon conversion generally would be expected to have higher conversion of the available coal sulfur or coal nitrogen to the vapor phase.

The ASTM standard methods were used to determine pyritic, sulfate and organic forms of sulfur present in the coal, ash and entrained particles for the three tests at the KRW PDU. For all three tests, total sulfur was enriched in the ash relative to the coal. Of the sulfur fractions in the ash, pyritic sulfur and sulfate were depleted and the organic sulfur fraction was significantly enriched relative to the coal. The pyritic and sulfate fractions are determined by dissolution in acids. The organic sulfur is a calculated value which is the difference between the measured acid soluble sulfur and the measured total sulfur. Therefore, the organic sulfur fraction is not analytically defined as being sulfur bound with hydrocarbon moieties but rather is an approximation of the acid insoluble sulfur present. The feed coal to the KRW gasifier is finely ground and subjected to bed temperatures over 800°C. Under this regime, it is difficult to view the insoluble sulfur fraction as truly organic sulfur. Relative to the feed coal, the total sulfur was depleted in the entrained particles for the bituminous and

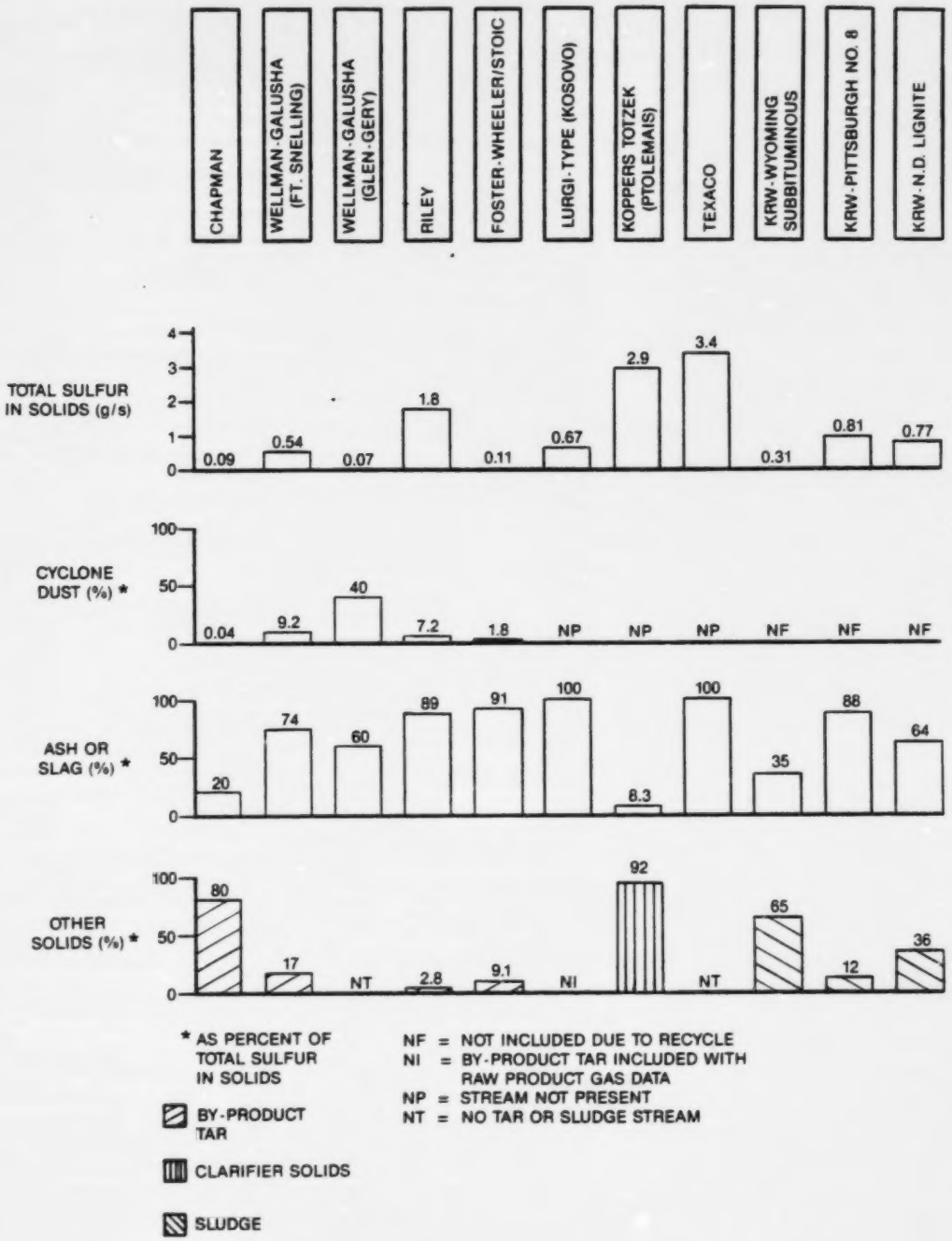


Figure 26. Distribution of sulfur in solid streams.

sub-bituminous tests and was enriched during the lignite test. Of the sulfur fractions, pyritic sulfur and sulfate were depleted and the insoluble (organic) sulfur was enriched. The data summarized here are given in Section 6.

The distribution of the outlet nitrogen in the process solids is summarized in Figure 27. Nitrogen was usually quite low in the entrained particles. The ash/slag contained the majority of the nitrogen exiting the process with the solids (over 60 percent). The tar-producing processes had significant percentages of the nitrogen present in the tars/oils. For example, nitrogen was not detected in the ash from the Chapman facility. It can be surmised for the Chapman gasifier that the preponderance of the coal nitrogen was present as relatively labile inorganic forms or bound in the organic phase of the coal since 82 percent of the measured nitrogen was in the tars and oils. Among the processes which did not produce tars/oils, the KRW data is interesting. Significant amounts of nitrogen were detected in the process sludge, amounts generally less than those exiting the process with the slag.

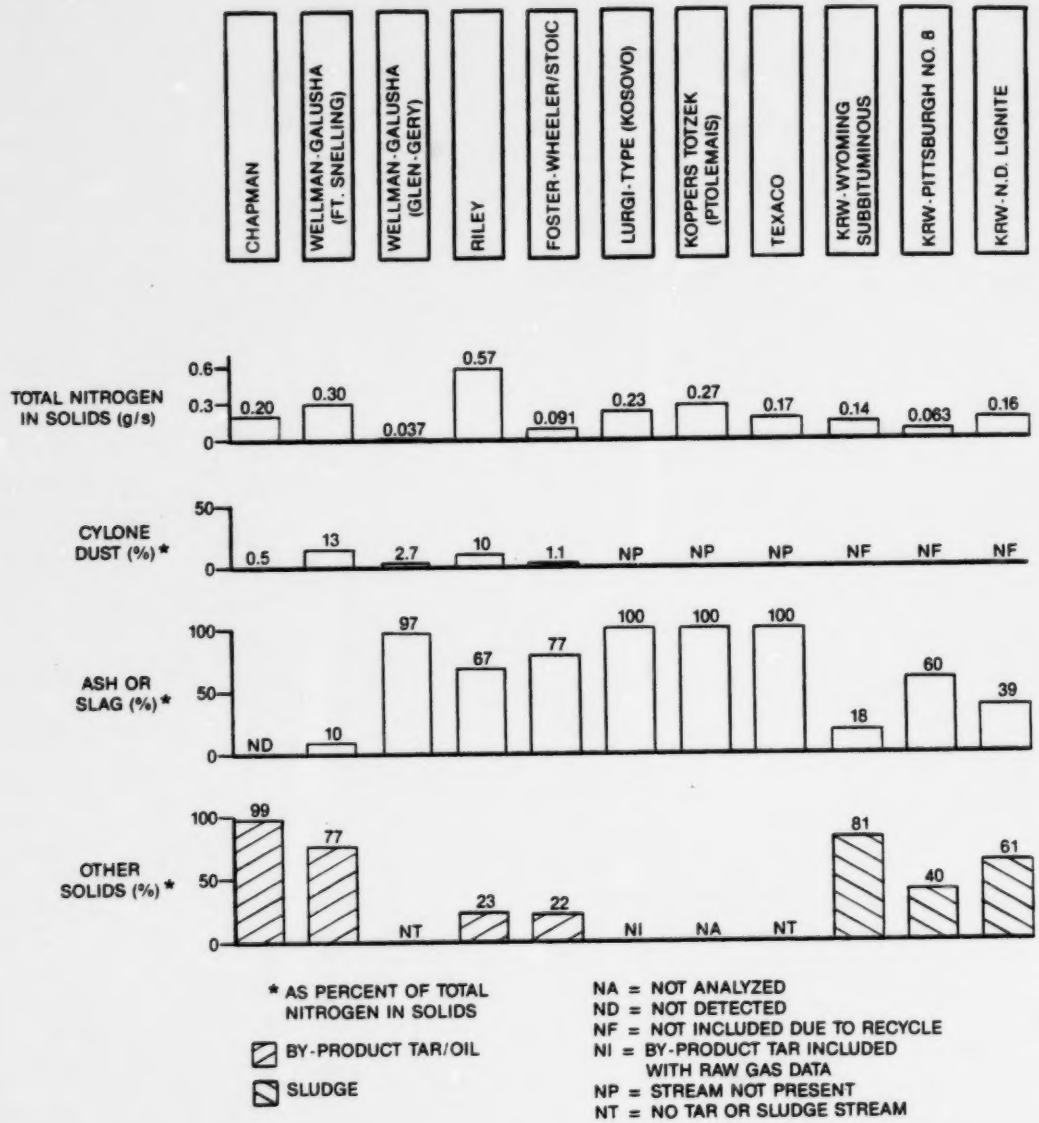


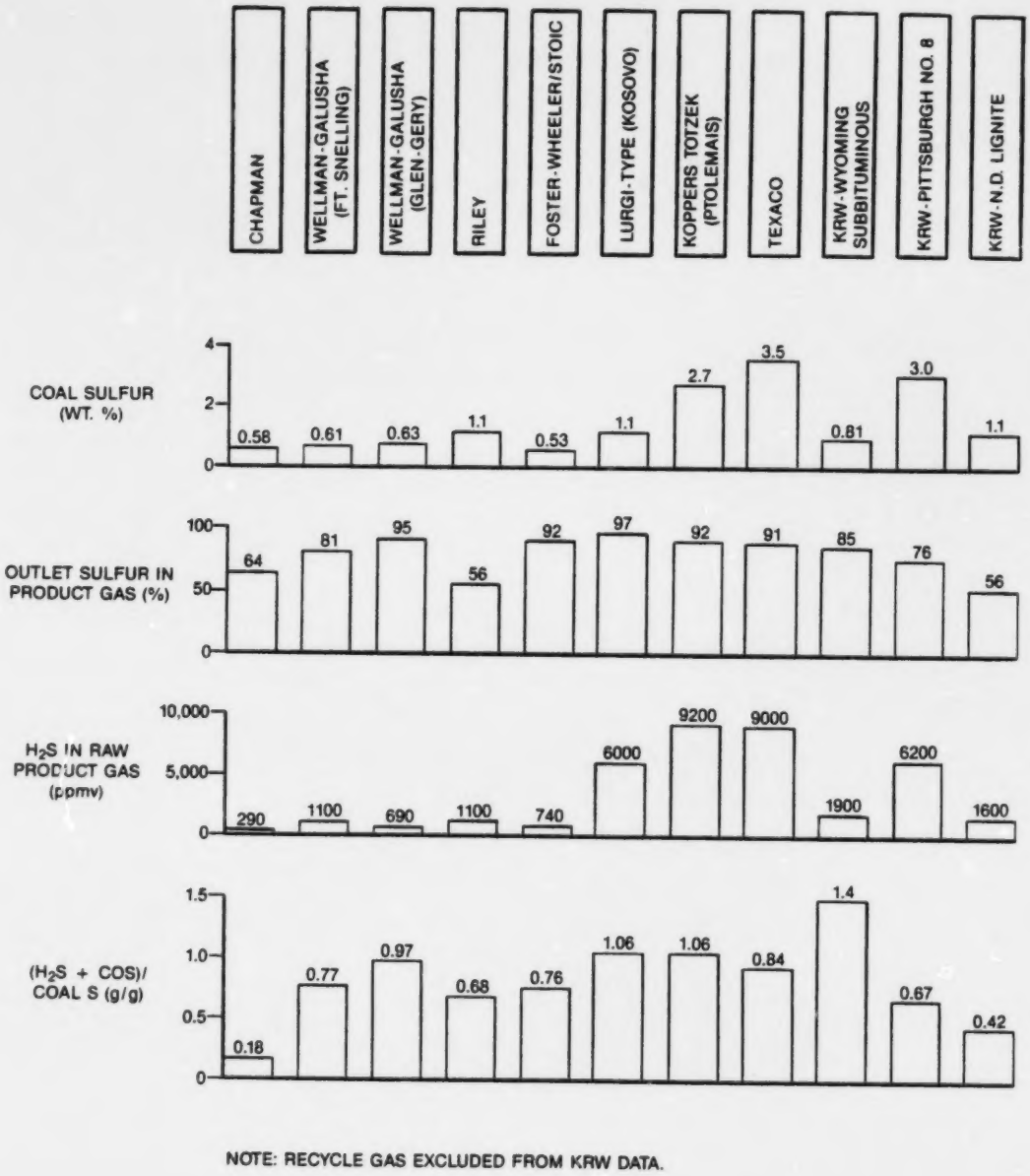
Figure 27. Distribution of nitrogen in solid streams.

SECTION 5

RELATIONSHIPS AND CORRELATIONS

The model relationships seen in data from laboratory and bench-scale parametric studies (11) are not quite as apparent in these source test data. The dynamics of actual plant operation and the variability in gasifier design, operating parameters such as temperature and pressure, and in the feed stream composition evidently contribute a "randomizing" effect on the predicted relationships when various processes are viewed as a group.

Some of the more popular assumptions which are not borne out totally by the measured data are the relationships between the composition of the feed coal and either the gas phase or the elemental content of the solids. Figure 28 shows the relationships between feed coal sulfur content and the hydrogen sulfide content (by volume) of the raw product gases. These data show that the atmospheric pressure fixed-bed gasifiers have lower hydrogen sulfide levels in the product gas than the oxygen-enriched processes; a general truism due to the high diluent nitrogen in those product gases. Figure 28 also summarizes the conversion of coal sulfur to hydrogen sulfide and carbonyl sulfide. These data show the more valid correlation that over approximately 70 percent of the coal sulfur will be volatilized during gasification. Therefore, higher coal sulfur will produce higher volatile sulfur levels but the effect of the diluent nitrogen in the product gas will partially obscure the relationship.



NOTE: RECYCLE GAS EXCLUDED FROM KRW DATA.

Figure 28. Relationship between coal sulfur and product gas sulfur.

Figure 29 shows the relationship between hydrogen sulfide and carbonyl sulfide in the raw product gases as well as the ratio of hydrogen sulfide to all other measured vapor phase sulfur species. Overall, the hydrogen sulfide/carbonyl sulfide ratios range from roughly 5 to 1 to 60 to 1. When all other measured volatile sulfur species are included, the range of the ratios narrows substantially to approximately five to ten parts hydrogen sulfide to one of any other volatile sulfur species. This 10 to 20 percent of the total volatile sulfur which is not hydrogen sulfide is significant since the behavior of some of the minor sulfur species in sulfur recovery/removal processes does not follow that of hydrogen sulfide. The included atmospheric pressure low-Btu processes have hydrogen sulfide present at a ratio of roughly nine or ten to one of carbonyl sulfide.

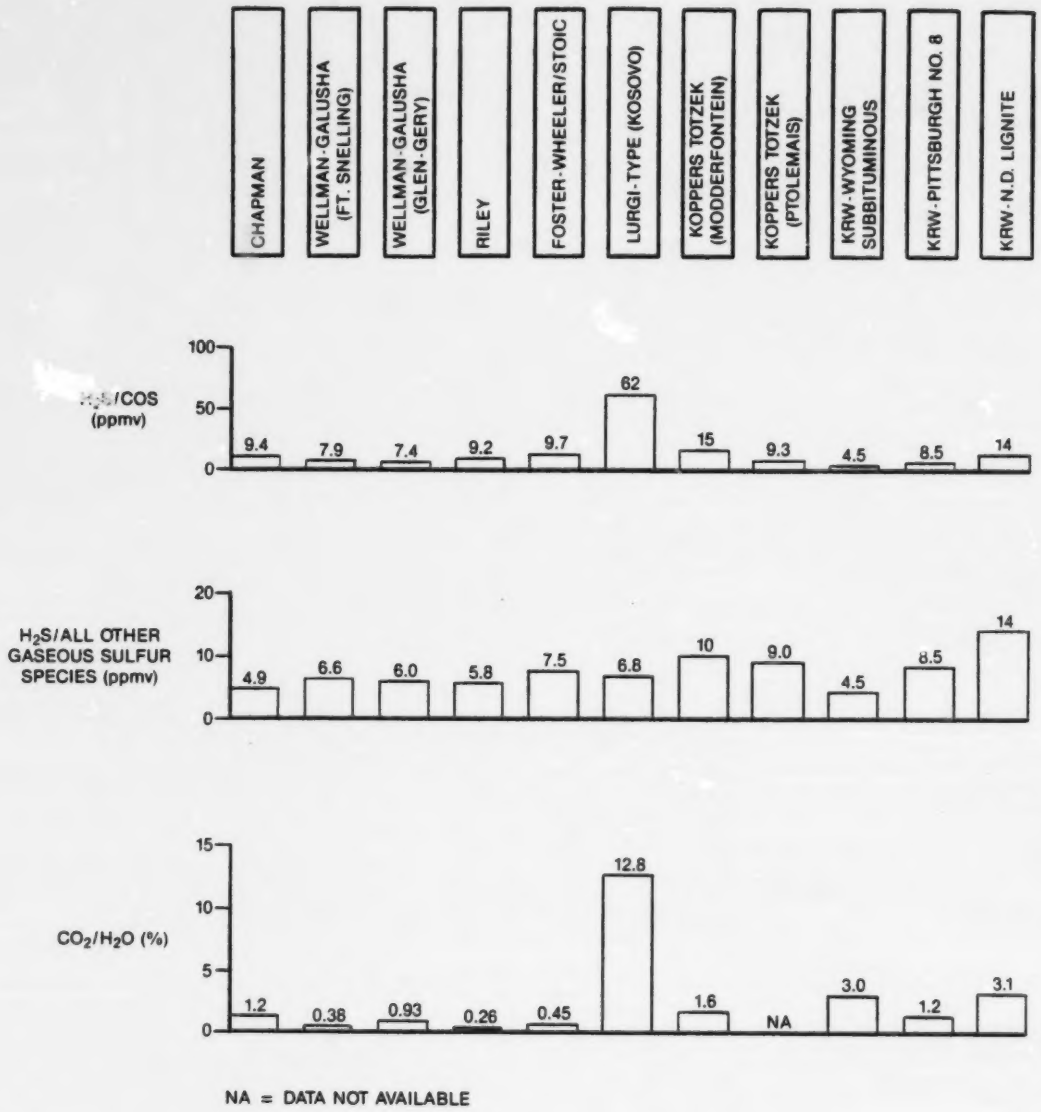
The conversion of carbonyl sulfide to hydrogen sulfide within the gasifier is limited by the hydrolysis reaction:

$$COS + H_2O \rightleftharpoons H_2S + CO_2$$

If hydrogen sulfide and carbonyl sulfide were at equilibrium, the H_2S/COS ratio would be related directly to the CO_2/H_2O ratio, also given in Figure 29, from the hydrolysis reaction by the equilibrium constant K_1:

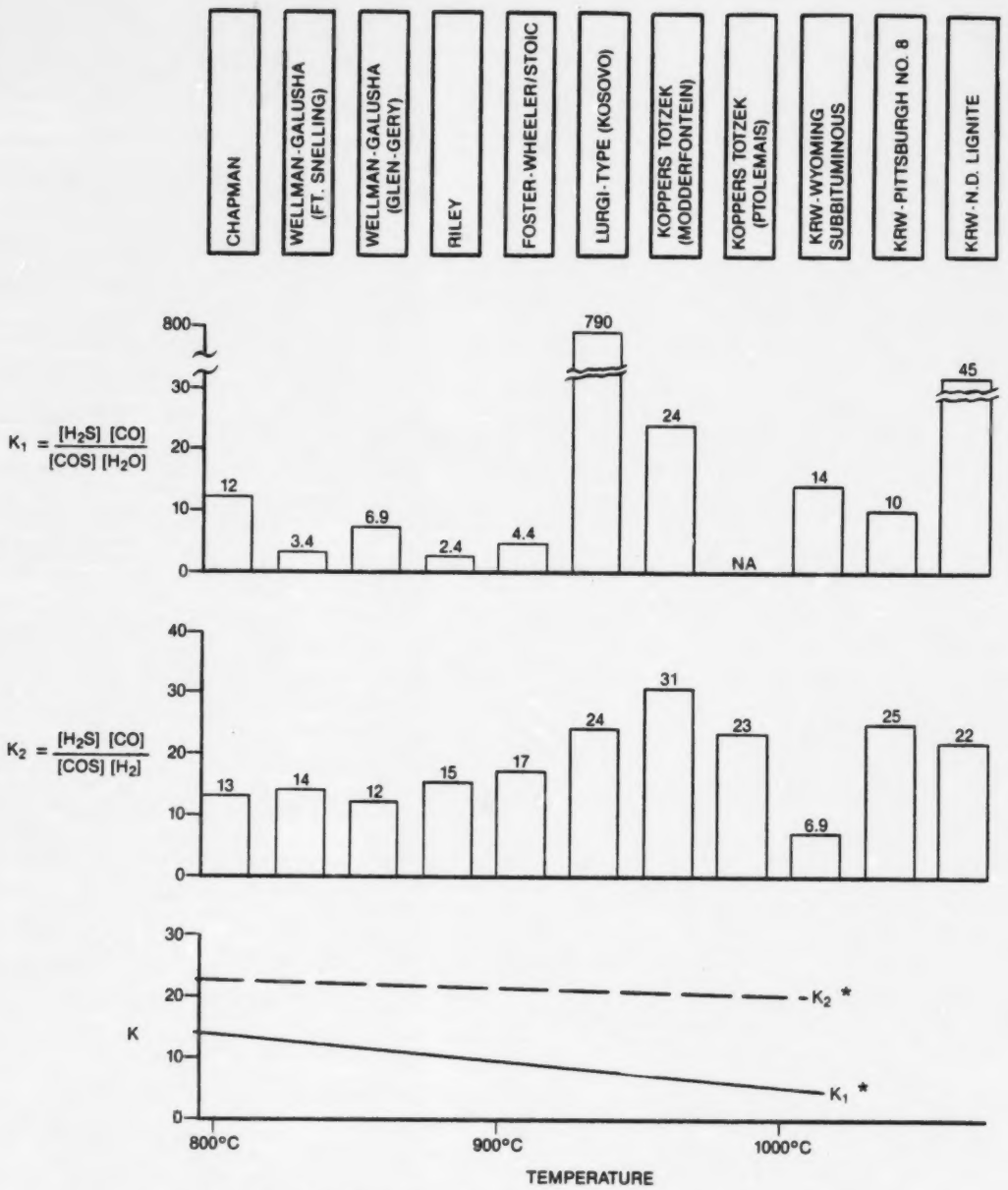
$$K_1 = \frac{[H_2S][CO_2]}{[COS][H_2O]}$$

Faist (12) observed that the major gas species concentrations, including H_2O and CO_2, most likely are frozen at equilibrium values corresponding to temperatures in the 600 to 1,000°C range. The actual ratios given in Figure 30 illustrate this being lower than the predicted equilibrium (K_1) for the temperature range.



NA = DATA NOT AVAILABLE

Figure 29. Product gas sulfur species comparisons.



* FROM FELDER AND FERRELL, "POLLUTANTS FROM COAL CONVERSION PROCESSES."

NA = DATA NOT AVAILABLE

Figure 30. Concentration ratios for hydrogen sulfide/carbonyl sulfide conversion reactions.

The equilibrium constant, K_1, decreases with increasing temperature which also favors H_2O and CO_2 production within the gasifier. Figure 30 gives the calculated K_1 values from each of the gasification processes and shows the temperature dependence (13) of K_1. The other conversion route for carbonyl sulfide to hydrogen sulfide is the hydrogenation reaction:

$$COS + H_2 \rightleftharpoons H_2S + CO$$

The equilibrium constant for this reaction, K_2, is defined as:

$$K_2 = \frac{[H_2S][CO]}{[COS][H_2]}$$

The values obtained for K_2 from the measured data are given also in Figure 30 along with the plot of the temperature dependence of K_2.

Production factors for hydrogen sulfide and carbonyl sulfide were determined for the gasification processes on two bases, grams of each species produced per gram of coal sulfur and grams of each species produced per gram of coal. Roughly 0.7 grams of hydrogen sulfide were produced for every gram of coal sulfur, although a moderately wide range of production factors was observed. The inherent uncertainty in some of the data may be exemplified by the KRW data for the gasification of Pittsburgh #8 which shows 1.3 grams hydrogen sulfide per gram of coal sulfur. Vapor phase production factors for the KRW-PDU have an associated uncertainty that may be greater than the other gasification facilities due to the recycling of raw product gas back through the gasifier by using the raw gas to pressurize/fluidize the pulverized feed coal. The mass flow of the inlet recycle gas was excluded from that of the outlet product gas to relate the product gas data directly to the elemental content of the coal. On the non-normalized basis, the average values were approximately 10 mg H_2S/g coal and 2 mg COS/g coal. These are within the range of values of 0.25 to 75 mg H_2S/g and 0.075 to 2.5 mg COS/g coal

obtained in parametric laboratory studies (14). The individual values are given in Figure 31.

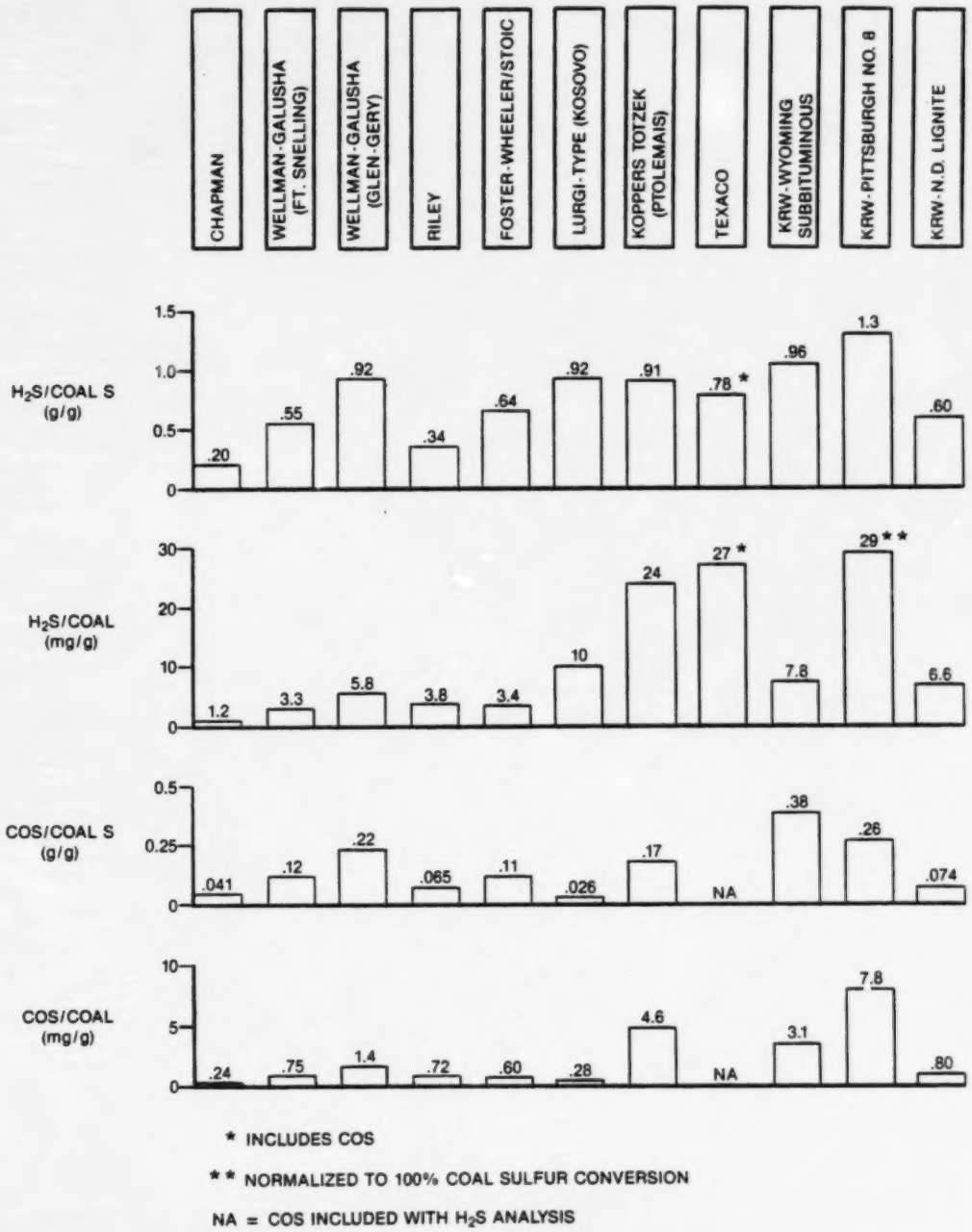
The ammonia and cyanide levels in the product gas are fairly constant relative to the total outlet coal nitrogen. As shown in Figure 32, for the processes which had raw product gas analysis of ammonia and cyanide prior to any aqueous quench/scrub; roughly 80 percent of the outlet coal nitrogen was present in the product gas as reduced nitrogen species. The KRW data is interesting in this case. Very low nitrogen accountability was achieved for the Pittsburgh #8 gasification test (29 percent over the facility, 59 percent for the gasifier module). However, the product gas accounts for 86 percent of the measured outlet nitrogen which is quite consistent with the sub-bituminous coal and lignite gasification tests. For the sub-bituminous coal and lignite tests, the ammonia and cyanide production factors are consistent (0.61 grams ammonia and cyanide and 0.64 grams ammonia and cyanide per gram coal nitrogen, respectively) but vapor phase nitrogen production for the Pittsburgh #8 was only 0.15 grams per gram coal nitrogen. At least three explanations of the Pittsburgh #8 coal test are readily apparent:

1) The Pittsburgh #8 nitrogen conversion was anomalously low,

2) Uncertainty in the product gas recycle mass flow due to the process configuration has introduced a bias in these data, or

3) A sampling/analysis error occurred.

The Pittsburgh #8 ammonia value may be suspect from the ratio of ammonia to cyanide compared with the two lower-rank coals (18:1 versus 110:1 and 57:1). Assuming the average ammonia/cyanide ratio from the low rank coal tests to hold for the Pittsburgh #8 and assuming the cyanide value to be valid, the ammonia concentration would be roughly 4000 ppmv. If 4000 ppmv ammonia were present in the raw product gas, the ammonia and cyanide production factor for the Pittsburgh #8 test would become 0.43 instead of 0.15 which would be more



* INCLUDES COS

** NORMALIZED TO 100% COAL SULFUR CONVERSION

NA = COS INCLUDED WITH H_2S ANALYSIS

Figure 31. Production factors, vapor phase sulfur.

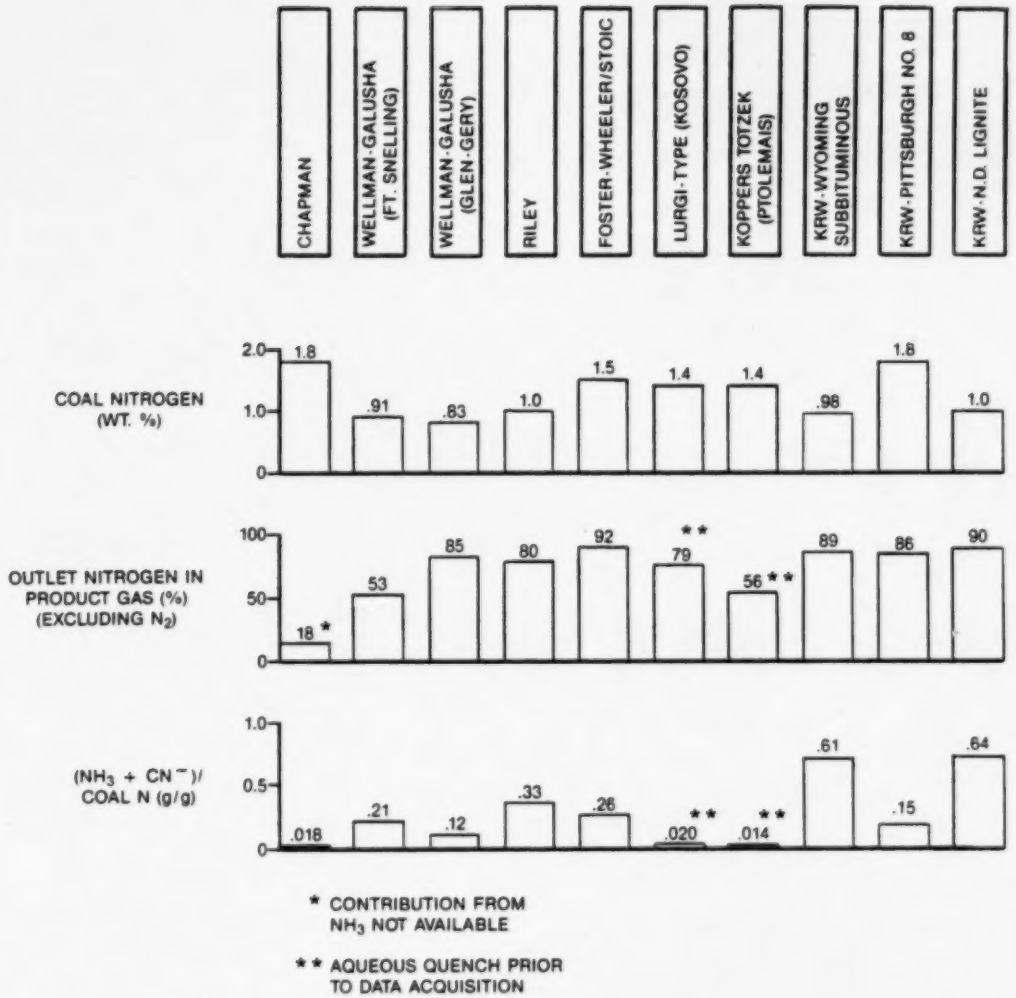


Figure 32. Relationship between coal nitrogen and product gas nitrogen.

consistent with the factors of 0.61 and 0.64 seen in the low-rank coal tests but certainly not so consistent as to be considered a proof of error.

Ammonia, the prevalent nitrogen species in the product gas, is about six times more abundant than cyanide in the atmospheric-pressure gasifiers as shown in Figure 33. Ammonia and cyanide production factors also fell within a fairly narrow range. About 300 mg of ammonia and 25 mg of cyanide per gram of coal nitrogen were produced in the unquenched product gas. Comparing these data to data from laboratory experiments on a per gram coal basis, the ammonia production factors were slightly higher and the production factors for cyanide were significantly higher than the experimental production factors of 0.01 to 2.5 mg NH_3/g coal and 0.008 to 0.1 mg HCN/g coal (14). These data from the individual process tests are given in Figure 34.

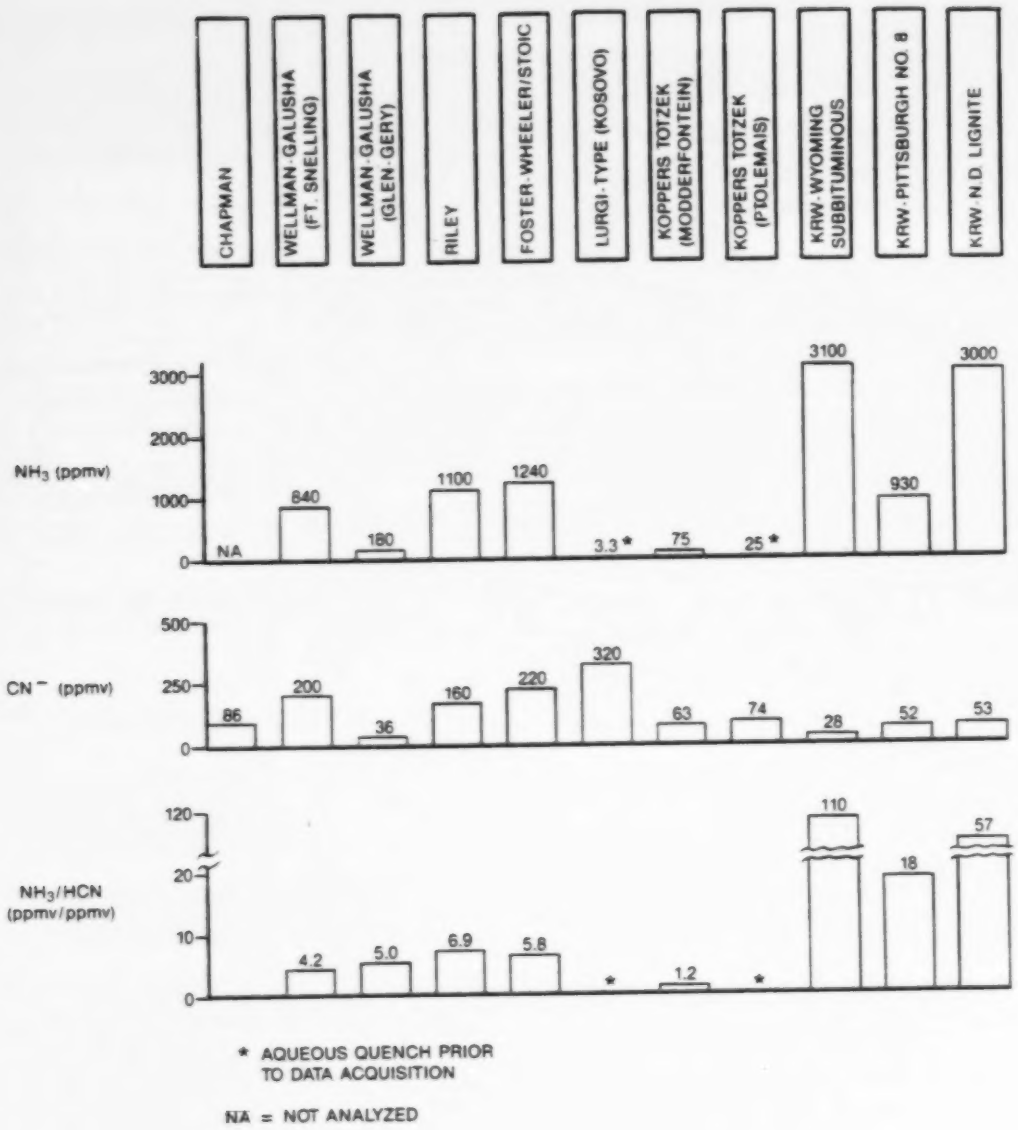


Figure 33. Product gas nitrogen species comparison.

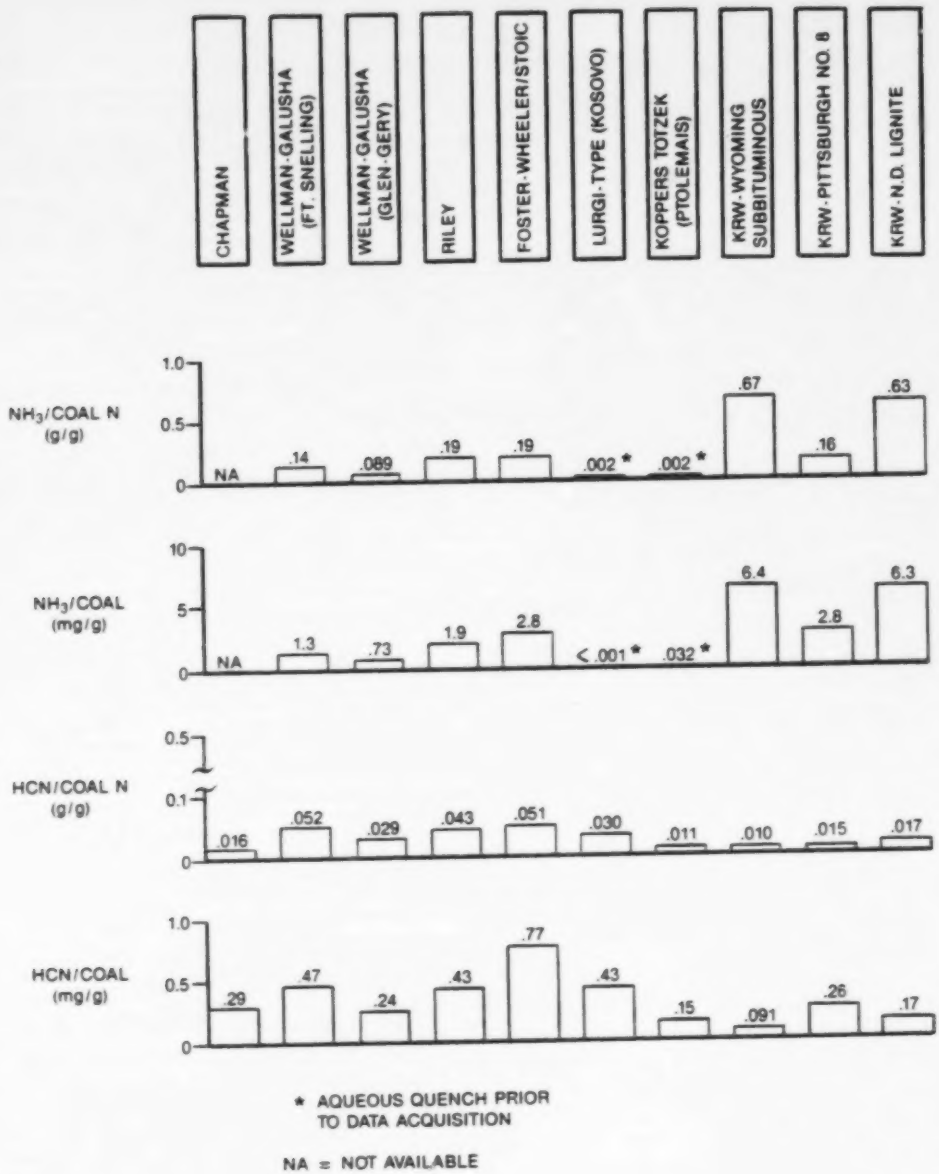


Figure 34. Production factors, vapor phase nitrogen.

SECTION 6

DATA SUMMARY

The data presented in the previous sections have been summarized from the values given in Tables 2 through 7 and the gasifier flow rate data which are appended. Tables 2 and 3 summarize the distribution of sulfur and nitrogen in the process streams from the facilities reviewed. Table 4 is the compilation of the vapor phase data for sulfur and nitrogen species. Table 5 is the summary of the aqueous stream data for both elements and Table 6 contains the sulfur and nitrogen concentrations in the solid streams. In collating the data for Tables 4 to 6, the average values or "best" data were selected. Some of these values were adjusted in previous work to provide better accountability for the elements. In general, the mass flow data given in Tables 2 and 3 were taken from the individual reference documents (1-10); therefore variations may be encountered in calculations using the average compositional data in Tables 4 through 6 relative to these mass flow data. The data given in Table 7 are the results from single analyses of solid samples collected during the operational 'steady state' periods at the KRW gasifier (10).

TABLE 2. SULFUR DISTRIBUTION[a]

	Chapman	Wellman-Galusha (Fort Snelling)	Wellman-Galusha (Glen Gery)	Riley	Foster Wheeler/ STOIC	Lurgi-Type (Kosovo)	Koppers-Totzek (Ptolemais)	Texaco[a] (Ruhrchemie)	KRW Pittsburgh #8 Bituminous	KRW WY Sub-bituminous	KRW ND Lignite
Coal Sulfur (%)	0.58	0.61	0.63	1.1	0.53	1.1	2.7	3.5	3.0	0.81	1.1
Sulfur Mass Flow (g/s-gasifier)											
Coal	0.80	2.7	1.4	3.2	1.4	39	47	62	4.2	1.5	2.4
Product Gas	0.16	2.1	1.4	2.3	1.1	47[b]	50	52	2.1[c]	0.87[c]	0.98[c]
Cyclone Dust	0.0004	0.05	0.028	0.13	0.002	d	2.7	d	0.088[e]	0.14[e]	0.36[e]
Ash or Slag	0.018	0.4	0.042	1.6	0.1	0.67	0.24	3.4[f]	0.71	0.11	0.49
By-Product Tar	0.072	0.09	d	0.05	0.01	g	d	d	d	d	d
Aqueous Discharges	h	h	h	h	i	0.14	0.70	1.6	0.076	0.063	0.038
Sludge	d	d	d	d	d	d	d	d	0.10	0.20	0.28
Other Gaseous Emissions	h	h	0.003[j]	h	h	0.71[k]	1	1	<0.001[m]	<0.001[m]	<0.001[m]

[a]Environmental test period #1: 14 November 1980. No settler underflow recycled.

[b]Crude product gas prior to cooling and tar/oil separation.

[c]Excluding recycle gas, 2.9 g/s bituminous test, 0.81 g/s sub-bituminous test, 0.91 g/s lignite test.

[d]Stream not present.

[e]Entrained particles in raw product gas. Flow rate for cyclone dust not available due to recycle configuration.

[f]Calculated by difference for elemental balance.

[g]By-product tar included in raw product gas.

[h]Measured flow data not available.

[i]Not analyzed.

[j]Pokehole gas, coal hopper gas.

[k]LP coal lock vent, HP coal lock vent, gas liquor tank vent, ash lock vent.

[l]Not reported.

[m]Coal lockhopper vent and ash lockhopper vent.

TABLE 3. NITROGEN DISTRIBUTION[a]

	Chapman	Wellman-Galusha (Fort Snelling)	Wellman-Galusha (Glen Gery)	Riley	Foster Wheeler/ STOIC	Lurgi-Type (Kosovo)	Koppers-Totzek (Ptolemais)	Texaco[a] (Ruhrchemie)	KRW Pittsburgh #8 Bituminous	KRW WY Sub-bituminous	KRW ND Lignite
Coal Nitrogen (%)	1.8	0.91	0.83	1.0	1.5	1.4	1.4	1.1	1.8	0.98	1.0
Nitrogen Mass Flow (g/s-gasifier)											
Coal	2.4	1.6	1.8	7	3.9	47	24	19	2.4	1.8	2.2
N_2 Feed	290	380	760	1170	470	28[b]	c	c	0.86[d]	2.0[d]	2.1[d]
Product Gas (Including N_2)	290	370	750	1180	530	39	0.39[e]	16.3	1.0	3.3	3.5
Product Gas (Excluding N_2)	0.044	0.34	0.21	2.3	1.0	0.94[f]	0.34	g	0.36	1.1	1.4
Cyclone Dust	0.001	0.04	0.001	0.06	0.001	c	g	c	0.038[h]	0.063[h]	0.063[h]
Ash or Slag	i	0.03	0.036	0.38	0.07	0.23	g	0.17[j]	0.038	0.025	0.063
By-Product Tar	0.2	0.23	c	0.13	0.02	k	c	c	c	c	g
Aqueous Discharges	1	1	1	1	1	0.002	0.27	1.8	j(0.006)	j(0.006)	j(0.006)
Sludge	c	c	c	c	c	c	c	c	0.025	0.11	0.10
Other Gaseous Emissions	1	1	<0.001[m]	1	1	0.023[n]	h	h	g	g	g

[a]Environmental test period #1: 14 November 1980. No settler underflow recycled.

[b]Nitrogen impurity in feed oxygen.

[c]Stream not present.

[d]N_2 in product gas recycled to gasifier.

[e]N_2 analysis of raw product gas includes Argon.

[f]Crude product gas prior to cooling and tar/oil separation.

[g]Not analyzed.

[h]Entrained particles in raw product gas. Flow rate for cyclone dust not available to recycle configuration.

[i]Not detected (approximate detection limit).

[j]Calculated by difference for elemental balance.

[k]By-product tar included in raw product gas.

[l]Measured flow data not available.

[m]Pokehole gas, coal hopper gas.

[n]LP coal lock vent, HP coal lock vent, gas liquor tank vent, ash lock vent.

TABLE 4. AVERAGE COMPOSITION: PRODUCT GAS

	CO_2	CO	CH_4	H_2	O_2	N_2	H_2O
Chapman	8.8	21.3	1.9	14.9	1.0[a]	54	7.0[b]
Wellman-Galusha (Fort Snelling)	9.5±1.8	26.3±4.6	1.3±0.3	15.4±2.4	0.7±0.4[a]	46.8±4.1	25
Wellman-Galusha (Glen-Gery)	5.5±0.28	25.5±1.8	0.23±0.03	16.3±0.65	0.9±0.2[a]	51.6±0.52	5.9±0.6
Riley	6.8±1	26±1.6	0.99±0.29	16±1.2	0.48±0.04 Ar=0.6±0.05	43±3.2	26±2.5
Foster-Wheeler/ STOIC	4.3±0.6	28.5±1.9	2.0±0.9	16±2.5	0.75	47±3.2	9.5±0.8
Lurgi-Type (Kosovo)	32	15	11.5	38.1	0.36	0.64	2.5
Koppers-Totzek (Modderfontein)	10.9	59.1	0.098	28.2	c	1.8[a]	6.7
Koppers-Totzek (Ptolemais)	9.4	62.2	10 ppmv	25.6	c	1.8[a]	c
Texaco (Ruhrchemie)	2.2	39.5	$CH_4+N_2<0.6$	37.5	d	$CH_4+N_2<0.6$	e
KRW							
Bituminous	37.5±1.7	44.6±2.6	2.0±0.7	15.2±2.4	0.3[a]	0.4±0.3	32
Sub-bituminous	33.6±2.3	35.7±3.8	6.0±1.0	23.5±1.0	0.1[a]	1.1±0.2	11
Lignite	30.8±1.2	39.0±1.6	4.0±0.2	25.5±0.3	0.1[a]	0.6±0.4	10

(Continued)

All concentrations in percent (dry gas basis) unless noted.

Where available, data from multiple samples is reported as average ± standard deviation.

[a]Includes argon.

[b]Estimated from partial data.

[c]Not reported.

[d]Not detected.

[e]Trace.

TABLE 4. (Continued)

	H_2S	COS	CH_3SH	CS_2	Other S	NH_3	HCN	Other N
Chapman	290	31	a	18	SO_2=10	a	86	NO=96-109
Wellman-Galusha (Fort Snelling)	1110±130	140±16	b(5)	12±4	SO_2=16±50	840±940	200±90	c
Wellman-Galusha (Glen-Gery)	690±150	93±17	a	0.8±0.6	SO_2=21±53	180	36	SCN=10
Riley	1110±330	120±20	57±35	5.3±1.8	$(CH_3)_2S$=6.4±3	1100±10	160±71	c
Foster-Wheeler/ STOIC	740±77	76±4	22±5.5	<1	C_2H_5SH<2	1240±82	220±29	c
Lurgi-Type (Kosovo)	6000	97	590	b(~8)	C_2H_5SH=200	3.3	320	c
Koppers-Totzek (Modderfontein)	4150	280	<0.5	130	SO_2=5	75	63	NO_x=8 (as NO_2)
Koppers-Totzek (Ptolemais)[d]	9200	990	c	24	SO_2=6	25	74	NO=3
Texaco (Ruhrchemie)	9000[e]	e	c	c	c	c	c	c
KRW								
Bituminous	6200±360	730±60	b(6)	b(3)	b(6)	930±180	52±16	SCN=53±34
Sub-bituminous	1900±450	420±60	b(1)	b(0.5)	b(2)	3100±1700	28±3.6	SCN=49±4.0
Lignite	1600±200	110±13	b(1)	b(0.5)	b(2)	3000±200	53±20	SCN=49±16

All concentrations in ppmv.

Where available, data from multiple samples is reported as average ± standard deviation.

[a]Not analyzed.

[b]Not detected (detection limit).

[c]Not reported.

[d]Raw product gas after primary gas quench.

[e]H_2S and COS reported as H_2S.

[f]Product gas downstream of quench (raw gas results for COS were approximately 1/2 of value obtained after quench).

TABLE 5. AVERAGE COMPOSITION: AQUEOUS DISCHARGES

	$SO_4^=$	$SO_3^=$	$S^=$	SCN^-	NH_3	CN^-	NO_3^-	NO_2^-	pH
Chapman									
[Separator Liquor][a]	1000	b	<0.01	<0.07	5000	1000	b	b	c
Wellman-Galusha (Fort Snelling)									
[Ash Quench]	2860	d	47[d]	b	5.4	<0.02	3	<0.01	9.3
[Cyclone Quench]	55	d	12[d]	b	0.97	0.36	<0.5[e]	<0.01	10.0
Wellman-Galusha (Glen-Gery)									
[Ash Quench]	95	b	3	2	3	0.06	17	b	c
Riley									
[Ash Quench]	1260	b	9.8	<4	<30	0.9	<0.02	b	10.8
Foster-Wheeler/STOIC									
[Ash Quench]	58	81	42	<4	<0.6	<0.08	2.7	b	12.5
Lurgi-Type (Kosovo)									
[Ash Quench]	495	f	f	0.03	1.9	<0.01	4.8	0.40	8.1
Koppers-Totzek (Ptolemais)									
[Washwater to Clarifier][g]	220	11	1	3	120	3.8	c	c	3.8
Texaco (Ruhrchemie)									
[Settler Underflow]	35	76	180	55	1320	28	≤0.75	<0.01	8.3
KRW									
[Wastewater Blowdown]									
Bituminous	330	18±6	14±12	120±23	910±50	45	4.0±3.5[h]	b	8.4
Sub-bituminous	160±90	11±1	27±14	84±8	1580±1210	33	6.2±0.44[h]	b	8.4
Lignite	180	12±1	46±15	92±16	3760±480	74	b	b	8.7
[Product Gas Quench Recycle]									
Bituminous	360±34	8.7±2.9	36±6.2	150±12	660±19	76±1.7	7.1±2.3[h]	b	7.0
Sub-bituminous	350±100	20±6.5	44±15	60±17	1180±100	23±5.4	9.7±2.5[h]	b	8.6
Lignite	120±11	16±0.47	69±13	88±19	2340±410	78±24	b	b	8.8
[Product Gas Cooler Recycle]									
Bituminous	b	9.7±2.9	110±10	55±13	1280±17	41±7.3	11±12[h]	b	7.7
Sub-bituminous	330±30	6±0	53±4.0	32±3.5	4090±260	39±5.0	5.3±2.0[h]	b	7.9
Lignite	27±19	7.3±2.0	91±43	33±2.0	5900±380	45±12	b	b	8.0

All concentrations ppm w/v (mg/L) except pH which is reported in pH units.

Where available, data from multiple samples reported as average ± standard deviation.

[a] Organic sulfur present at 550 mg/L.

[b] Not analyzed.

[c] Not reported.

[d] Sulfite and sulfide reported as sulfide.

[e] Interference present.

[f] Trace.

[g] $S_2O_3^=$ present at 83 mg/L.

[h] Nitrate and nitrite reported as nitrate.

TABLE 6. AVERAGE COMPOSITION: SOLIDS

	Ash or Slag		Cyclone Dust		Feed Coal	
	Sulfur	Nitrogen	Sulfur	Nitrogen	Sulfur	Nitrogen
Chapman	0.21	[a]	0.7	1.7	0.58	1.8
Wellman-Galusha (Fort Snelling)	1.1	0.17	1.5	0.93	0.61	0.91
Wellman-Galusha (Glen-Gery)	0.2	0.18	1.5	0.62	0.63	0.83
Riley	1.3	0.32	1.6	0.81	1.1	1.0
Foster Wheeler/STOIC	0.28	0.19	1.0	0.72	0.53	1.5
Lurgi-Type (Kosovo)	0.15	0.03	[b]	[b]	1.1	1.4
Koppers-Totzek (Ptolemais)	0.3[c]	[d]	1.3[c]	[d]	2.7	1.4
Texaco (Ruhrchemie)	2.4	1.0	2.8[e]	1.4[e]	3.5	1.1
KRW						
Bituminous	4.4±0.57	0.22±0.18	2.4(1.7)[1.6][f]	0.54(0.46)[0.50][f]	3.0	1.8
Sub-bituminous	0.96±0.19	0.26±0.05	0.51(0.48)[0.85][f]	0.48(0.27)[0.50][f]	0.81	0.98
Lignite	3.1±1.3	0.43±0.36	2.0(2.1)[1.6][f]	0.49(0.46)[0.60][f]	1.1	1.0

Data in weight %, dry basis.

Where available, data from multiple samples reported as average ± standard deviation.

[a]Not detected.

[b]Stream not present.

[c]Solids in wash water.

[d]Not reported.

[e]Settler fines.

[f]Primary cyclone (secondary cyclone) [sludge]. Cyclone dust is recycled. Sludge is collection and disposal point for entrained solids removed after cyclones by quench/scrubbing.

TABLE 7. SULFUR SPECIATION OF SOLIDS FROM THE KRW PDU

	Pyritic Sulfur	Sulfate Sulfur	Organic Sulfur[a]	Total Sulfur
Feedstock				
Pittsburgh #8 bituminous	0.89	0.04	2.22	3.15
	1.28	0.05	2.11	3.44
	0.89	0.04	2.14	3.07
Wyoming sub-bituminous	0.20	0.03	0.57	0.80
	0.20	0.02	0.59	0.81
	0.24	0.02	0.57	0.83
North Dakota lignite	0.32	0.06	0.63	0.01
	0.25	0.06	0.71	1.02
Ash				
Pittsburgh #8 bituminous	0.24	b	4.41	4.65
	0.19	b	5.04	5.23
	0.28	0.01	3.82	4.11
Wyoming sub-bituminous	0.15	0.02	0.64	0.81
	0.21	b	0.75	0.96
North Dakota lignite	0.72	b	4.01	4.83
	0.74	b	1.82	2.56
	0.09	b	2.41	2.50
Entrained Particles				
Pittsburgh #8 bituminous	b	0.01	1.43	1.44
Wyoming sub-bituminous	0.07	0.04	0.56	0.67
North Dakota lignite	0.11	0.11	1.97	2.18
Sludge				
Pittsburgh #8 bituminous	0.01	0.10	1.97	2.18
Wyoming sub-bituminous	c	c	c	c
North Dakota lignite	c	c	c	c

All data in % (by weight) dry basis.

[a]Determined by difference; Total sulfur - (pyritic sulfur + sulfate sulfur) = "organic" sulfur.

[b]Less than 0.01.

[c]Not analyzed.

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APPENDIX

GASIFIER FLOW RATE DATA

TABLE A-1. CHAPMAN GASIFIER STREAM FLOW RATE DATA

Stream	Flow rate, g/s-gasifier[a]
Inputs:	
Coal	152
Air	385
Steam (water vapor)	80
Outputs:	
Cooled product gas	495
Gasifier ash (dry basis)	9.3
Cyclone dust	0.8
By-product tar	15

[a]Average for the two operating gasifiers.
Source: Ref. 1.

TABLE A-2. WELLMAN-GALUSHA (FORT SNELLING) GASIFIER STREAM FLOW RATE DATA

Stream	Flow rate, g/s-gasifier	
	Sampling Period One	Sampling Period Two
Inputs:		
Coal	320 ± 28	250 ± 21
Air	500 ± 55	444 ± 49
Steam (water vapor)	67 ± 8.4	66 ± 8.3
Outputs:		
Dry product gas	720 ± 63	570 ± 49
Product gas moisture	130 ± 16	120 ± 15
Tar	12 ± 1.4	9.8 ± 1.1
Gasifier ash	27 ± 2.8	21 ± 2.1
Cyclone dust	3.8 ± 1.3	—
Gasifier ash sluice water	~7	~7
Cyclone dust quench water	<7	

Source: Ref. 3.

TABLE A-3. WELLMAN-GALUSHA (GLEN-GERY) STREAM FLOW RATE DATA

Stream	Flow rate, g/s-gasifier
Inputs:	
Coal	219
Air	992
Steam (water vapor)	194
Outputs:	
Product gas	1,333
Gasifier ash	20.6
Cyclone dust	0.2
Coal hopper gas	2.2
Pokehole gas	1.7

Source: Ref. 2.

TABLE A-4. RILEY GASIFIER STREAM FLOW RATE DATA

Stream	Flow rate, g/s-gasifier
Inputs:	
Coal (including moisture)	1,000 ± 109
Air	1,200 ± 240
Steam	350 ± 88
Service water	2,200 ± 440
Outputs:	
Product gas (dry basis)	2,300 ± 230
Moisture in gas	620 ± 61
Gasifier ash	75 ± 30
Cyclone dust	4 ± 1
Tars and oils	21 ± 4
Ash pan water	2,200 ± 440

Source: Ref. 4.

TABLE A-5. FOSTER-WHEELER/STOIC GASIFIER STREAM FLOW RATE DATA

Stream	Flow rate, g/s-gasifier
Inputs:	
Coal (including moisture)	300 ± 30
Air	620 ± 120
Steam (water vapor)	70 ± 7
Ash pan makeup water	7 ± 4
Lock hopper purge steam	16 ± 4
Pokehole purge steam	6 ± 2
Outputs:	
Combined product gas (dry basis)	930 ± 190
Moisture in product gas	75 ± 15
Gasifier ash	35 ± 4
Moisture in gasifier ash	9 ± 0.9
Cyclone dust	0.2 ± 0.1
ESP oil	4 ± 1

Source: Ref. 5.

TABLE A-6. LURGI-TYPE GASIFIER STREAM FLOW RATE DATA

Stream	Flow rate, g/s-gasifier
COAL PREPARATION	
Run-of-mine coal	6,667
Dryer offgas (dry basis)	22
Dryer condensate	-
Dried coal	4,444
GASIFICATION/GAS QUENCH	
Dried coal	4,444
Oxygen	778
Steam	3,611
High pressure coal lock vent (dry basis)	65
Low pressure coal lock vent (dry basis)	5.6
Ash lock cyclone vent (dry basis)	12.4
Wet ash	750
Ash quench wastewater	720
Crude gas (dry basis)	4,675
RECTISOL AGR	
Crude gas (dry basis)	4,675
Clean product gas (dry basis)	1,275
H_2S-rich offgas (dry basis)	1,758
CO_2-rich offgas (dry basis)	1,725
Cyanic water	172
Naphtha	36
GAS LIQUOR SEPARATION	
Cyanic water	172
Heavy tar	28
Waste gas (dry basis)	12.4
Medium oil	69
Light tar	111
Phenolic water	3,611
PHENOSOLVAN/STRIPPING	
Phenolic water	3,611
Crude phenol	25
NH_3 stripper vent gas	96.5

Source: Ref. 6.

TABLE A-7. KRW PDU GASIFIER STREAM FLOW DATA

Stream	Flow Rate, g/s-gasifier		
	Test 1 Wyoming Subbituminous	Test 2 Pittsburgh No. 8	Test 3 North Dakota Lignite
Inputs			
Coal	219.2	141.0	271.6
Steam	56.8	73.4	67.2
Oxygen	112.8	145.3	135.6
CO_2 to gasifier	50.8	65.7	49.2
H_2O injection	0.0	150.3	0.0
Coal lockhopper gas (CO_2)	4.0	2.6	5.0
Ash lockhopper gas (CO_2)	1.7	1.7	1.7
Makeup water	479.4	207.9	161.3
Outputs			
Scrubbed and cooled product gas	364.0	321.9	453.8
Gasifier ash	11.6	16.0	15.6
Wastewater	506.1	408.1	202.4
Sludge	51.8	13.8	37.7
Coal lockhopper vent	3.5	2.3	4.2
Ash lockhopper vent	1.7	1.7	1.7

Source: Ref. 10.

TABLE A-8. KOPPERS-TOTZEK GASIFIER STREAM FLOW RATE DATA

Stream	Flow Rate, g/s-gasifier
Inputs:	
Pulverized coal	1,750
Oxygen	1,640
Steam	175
Outputs:	
Raw gas (dry)	3,110
Slag	80
Discharge water	2,275
Fly ash (dry)	210

Source: Ref. 7.

TABLE A-9. TEXACO GASIFIER STREAM FLOW RATE DATA

Stream	Flow rate, g/s-gasifier	
	Period One[a]	Period Two[b]
Inputs:		
Coal (dry basis)	1,690	1,634
Oxygen	1,564	1,561
Fresh water[c]	1,319	347
Demineralized water	1,424	1,278
Outputs:		
Scrubbed synthesis gas	3,221	3,206
Slag	570	501
Flash gas	7.5	8.3
Settler underflow-blowdown	2,141	1,029

[a]No recycle of clarifier underflow.
[b]Minimization of fresh water makeup by recycle of clarifier underflow.
[c]Includes water in coal feed, additive mixture, and flocculant mixture.
Source: Ref. 9.